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# The Application of Advanced Information Technology in Assessing Environmental Impacts

**Michael F. Goodchild**

*National Center for Geographic Information Analysis*
*University of California*
*Santa Barbara, California*

## ABSTRACT

Although many advanced information technologies are potentially of value to environmental impact assessment, this chapter focuses on those generally included under the term geographic information technologies, including geographic information systems (GIS), remote sensing, and the global positioning system (GPS). The chapter begins with a brief description of each of these, and a more detailed review of the state of development of GIS, its current capabilities, and impediments to greater use. Problems having to do with the integration of the geographic information technologies, and the raster and vector approaches to GIS, are discussed in the context of non-point-source pollution in the vadose zone, and attention is drawn to current research on advanced geographic data models, which may hold the key to further progress in integration.

Modern assessment of environmental impacts makes use of a variety of information technologies, from word processing and spreadsheets to geographic information systems. Some of these are by now so widely applied in all aspects of human activity that they scarcely bear mention in a volume of this nature. Others, however, are still at the lower end of the growth curve both in terms of applications, and also in terms of their influence as tools on the way science and assessment are conducted. The geographic information technologies seem to fall in this latter category, which is one reason for raising them to prominence in this volume.

The singling out of geographic information technologies may seem odd to someone not already familiar with them. It is not common, for example, to organize conferences on textual information in environmental science, or on the use of photographic images. Geographic information can be defined as facts that are tied to specific locations on the Earth's surface, but the presence of geographic coordinates in data hardly seems to justify special attention. But there are sever-

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al strong arguments for special treatment for spatial data. First, the real world is infinitely complex, so any digital representation must be an approximation. Moreover, in general an infinite number of alternative representations exist for any real geographic phenomenon. Second, geographic data tend to be particularly voluminous, and for a variety of practical reasons generally incompatible with other information types. Finally, there appears to be a very strong distinction between conventional digital structures of geographic data and the ways people actually think and reason about space (Mark & Frank, 1991).

A variety of technologies for collecting, handling, and analyzing spatial data have emerged in the past three decades. If attention is limited to those that deal strictly with geographical data, rather than the more generally defined spatial data, then the list would have to include GPS, the global positioning system based on analysis of signals from a constellation of orbiting satellites; electronic surveying technology as typified by the modern total station; remote sensing; and GIS. Of the four, the second seems least appropriate in the context of environmental impact assessment.

The GPS is perhaps the most straightforward, if viewed as a technology for providing measurements of the geographic positions of points, although a range of approaches exist with associated accuracies, and there are many challenging technical issues in the system's design (Leick, 1990). From the perspective of the field scientist, however, the current capabilities of GPS as a source of accurate positions in the field can be summarized fairly simply. With a hand-held receiver costing around $300, estimated locations will be within 100 m of true position about 90% of the time. If the receiver is able to receive uncorrupted signal (such receivers currently cost about $1500 and are available to the military and certain federal agencies), then the corresponding accuracy measure is about 32 m. If GPS is used differentially (DGPS), either by investing about $10,000 in a base station and radio transmitter placed at a fixed, known location, or by subscribing to one of a number of commercial sources of correction signals via a pager, phone, or Internet, then accuracies as high as 1 m are achievable.

Although remote sensing can be broadly defined as measurement at a distance, for most purposes it implies the imaging of the surface of the Earth from an airborne or space-borne sensor, using some appropriate part of the electromagnetic spectrum. The technical issues of sensor design, orbital corrections, cloud, and noise reduction are not of concern here. Remote sensing software is designed to process this raw data into forms that are useful for a range of purposes, from simple mapping and monitoring to management and modeling.

Remotely sensed data has a range of potential uses in addressing the problems of non-point-source pollution in the vadose zone. Simple high-resolution imagery provides a useful form of base map if suitably corrected to vertical perspective. The Digital Orthophoto Quadrangle (DOQ) program of the U.S. Geological Survey (for further information on the DOQ program see the WWW home page http://nsdi.usgs.gov/nsdi/products/doq.html) is providing coverage of areas of the continental USA in digital form with 1 m resolution and 6 m positional accuracy, and similar resolutions are becoming available from commercial satellite systems, and from other countries.

Besides mapping, remote sensing also is useful as a direct source of measurements of relevance to the vadose zone. By sensing particular parts of the electromagnetic spectrum, it is possible to detect a range of physical and biological surface conditions, such as soil moisture or vegetation cover. The temporal sampling interval of these systems is sufficiently short to make them useful for detecting change in these parameters, and instruments with very high spectral resolution, such as AVIRIS, can support detailed modeling of surface physics. Further details on applications of remote sensing to non-point-source pollution in the vadose zone are beyond the scope of this chapter. The interested reader is referred to standard texts and journals on the subject and to the chapters by Corwin (1996, this publication) and Jaynes (1996, this publication).

A geographic information system is a much broader and more nebulous concept—a system for the input, storage, manipulation, and output of geographically referenced data. Although there is wide acceptance of this general definition (for a review of GIS definitions see Maguire, 1991), the actual specification of a GIS can vary widely depending on the assumptions that its designers are willing to make about its uses. For example, a GIS designed to process only data derived by remote sensing would be very different from one designed to process only data derived from maps. This chapter will not attempt to provide a general introduction to GIS, since the topic is already addressed comprehensively in many texts (for general overviews see Burrough, 1986; Maguire et al., 1991; Star & Estes, 1991). Goodchild et al. (1993) include several chapters on the use of GIS in hydrology.

The value of the geographic information technologies in a field like environmental impact assessment will ultimately depend on whether the technology can find useful application. The functions performed by the technology must match those needed by the application, and in this sense technologies like GIS, which have been designed for very general purpose manipulation of geographic data, are likely to be successful; however, given the fundamental diversity inherent in the representation of geographic phenomena noted earlier, it also is important that the representations adopted within GIS also match those used by the application. The next section reviews the state of the art and recent research on issues of representation in the geographic information technologies, or what is more appropriately defined as geographic data modeling, and comments on the compatibility between GIS data models and those that commonly underlie modeling in the vadose zone.

## GEOGRAPHIC DATA MODELING

In recent years, the field of geographic data modeling has emerged as a distinct and important subspecialty of geographic information science, and is now recognized as one of, if not the most fundamental of the research issues raised by the development and exploitation of geographic information systems. Geographic data modeling can be seen as a subfield of data modeling in general, and also as a subset of the broader issues of geographic representation—the systematic study of the methods people use to create representations and understandings of the world around them.

At this point, it is perhaps worth stressing the distinction being made here between geographic data modeling, and the modeling of processes operating on or under the geographic landscape. In the first case the emphasis is on representation, and the choices that must be made to create a discrete digital version of some real geographic form or pattern. Process modeling, on the other hand, is concerned with the mathematical or numerical representation of processes rather than forms, and with prediction and understanding rather than with representation per se.

The relationship between these two forms of modeling is complex, and its importance is often overlooked. Models of process are often written in continuous spaces; the Navier–Stokes equation, for example, is written in partial derivatives with respect to the spatial and temporal dimensions. Unless analytic solutions are available, such models must be approximated in discrete form, most often by discretizing the spatial and temporal dimensions. The finite element or finite difference models that result are numerical approximations to the original continuous models. In addition, process modelers often work with lumped models, in which the discrete space–time elements are arbitrarily shaped objects, and processes are modeled as occurring either between objects, or uniformly within objects.

At a conceptual level, the process known in GIS as geographic data modeling and the processes of discretization and numerical approximation in environmental modeling are roughly equivalent. The choice of a finite difference discretization is equivalent to the choice of a raster data model in GIS; finite element discretizations are often similar to the polygon and triangulated irregular network models of GIS. Thus data modeling is an essential preliminary to environmental modeling, although it may not be known by that name. The representational choices made will undoubtedly influence the way scientific investigation is ultimately carried out, and the quality of its analyses and predictions.

Peuquet published a comparatively early and much cited review of geographic data modeling (Peuquet, 1984). Goodchild (1992) provides a more recent review, and the increasing importance of the field is reflected in the chapters devoted to this topic in the review of GIS by Maguire et al. (1991). Notable among more specialized reviews are the discussions of modeling the temporal component in spatial databases by Langran (1992) and Peuquet (1994), and of three dimensional spatial information by Raper (1989) and Turner (1992). Smith et al. (1994) demonstrate the importance of geographic data modeling in environmental science, giving examples of the role data models can play in the formulation and use of mathematical models of environmental systems and processes.

Data modeling is a complex and often subtle process that extends from the design of surveys and instruments for capturing raw data through the various manipulations that occur before the data are finally ready to be analyzed or displayed. For example, we have traditionally monitored the Earth's spatio-temporal precipitation field by continuous sampling at an international network of weather stations. Each station reports its time series using a variety of aggregation intervals. A variety of techniques are commonly used to interpolate the field spatially between sample points. Each of these sampling and processing decisions ultimately affect how the world is represented in the digital database, and constrain the kinds of analysis that can be performed, but they are made at different times, by different people, and perhaps with different objectives in mind.

The next section provides a review of the use of traditional geographic data models, and is followed by a discussion of recent research on advanced data modeling, and its potential applications in this area. While many of these developments have yet to be implemented across the full range of available software products, their eventual availability is likely to have a substantial impact, in changing the ways in which hydrologists and others collect and represent geographic data, and structure models of processes.

## TRADITIONAL GIS DATA MODELS

Traditionally, GIS data models have been divided into two major classes: *raster* data models, which appear in finite difference models and represent two-dimensional spatial variation by assigning values to cells in a fixed rectangular array; and *vector* data models, which represent spatial variation through irregularly distributed points, lines, and areas. Lines and area boundaries are often conceived as smoothly varying, but the vector data models represent both as connected sequences of straight segments (*polylines* and *polygons* respectively), although some systems, particularly those developed to handle land ownership or *cadastral* data, also support smooth representations known as *splines*, and also connected arcs of circles. In a raster model, each cell in an array is normally restricted to a single value, so multiple *layers* of coincident cells must be used to represent the spatial variation of many variables. For example, a layer might represent the spatial variation of depth to groundwater in a layer constructed by *interpolating* between a number of measurement locations.

The meaning of *layer* for vector systems is more complex. For some systems, a layer is simply a convenient grouping of one or more classes of points, lines, or areas; a layer might include all roads, for example, or all county boundaries. In such systems, organization of the data into layers facilitates display, allowing the user to turn layers on or off, and assign them different colors or other types of symbolization. In other systems, the points, lines, or areas forming a layer must be *planar enforced.* In the case of a layer of areas, this means that areas cannot overlap and must fill the project area, so that every location within the project area lies in exactly one area. This is true in general of many classes of statistical reporting zones, such as counties, and also of land ownership.

Because of this confusion, and wide variation in the constraints placed by designers of GIS on how geographic phenomena can be modeled in their databases, there have been several attempts to provide an overarching conceptual framework that can accommodate the various implementations found among available GIS and spatial database products. Goodchild (1992) argues that two views of spatial variation underlie the various options. One is a *field,* defined as the view that a variable can be given a single, well-defined value at every location within the project area. An example of a field variable is *elevation.* Many systems of statistical reporting are defined by assigning each location to a single zone, for example, each point in the USA lies in exactly one county (if we ignore the possibility of lying exactly on a boundary), and in exactly one hydrologic response unit at any given level in the drainage basin hierarchy. Counties and hydrologic response units (HRUs) thus satisfy the definition of a field, because they assign every location to a single value, measured in these cases on a nominal scale as an identifying name.

While elevation and county satisfy the definition of fields, other spatial variables raise problems. It is not immediately obvious that point sources of pollutants, for example, can be conceived as fields. Pollutant density can be defined for a county by dividing total pollutant load by area, but this definition breaks down as the area of the reporting zone shrinks, and becomes meaningless for areas below perhaps 1 km in diameter, depending on the context. But this problem can be avoided in two readily available ways. First, we could define pollutant density as a field by specifying an explicit search radius, for example, value at a point could be defined as the ratio of the total pollutant load found within 1 km of the point divided by the area of a circle of radius 1 km. Second, we could make use of techniques of density estimation, which replace discrete point locations with a spatially continuous *kernel function* (Silverman, 1986). Within the geographical literature density estimation is analogous to the calculation of potential (see i.e., Stewart, 1947).

For spatial variation conceived or characterized as a collection of fields, spatial databases currently provide six distinct methods of discrete, digital representation. The six field data models are:

- a regular rectangular array of cells, with the average value of the field recorded in each (*raster* model);
- a regular rectangular array of sample points (*grid* model);
- an irregularly spaced set of sample points (*point* model);
- a polyline representation of a set of isolines (*contour* model);
- a set of planar enforced irregular polygons, with associated average values for each (*polygon* model);
- a set of planar enforced irregular triangles, variation within each triangle being assumed to be planar (*triangulated irregular network* or *TIN* model).

Since the average or mean value cannot be defined for nominal-scaled data, it is normally replaced with the modal or commonest value, although in many cases the nominal value will be true for the entire cell or polygon (e.g., county name). The names suggested above are conventional, although many equivalent terms exist.

Although there is clear equivalence between finite difference approximations and the raster model (and possibly the grid model), the equivalence to finite element approximations is not as clear. The TIN model uses a linear model to describe within-element variation, thus achieving zero-order continuity across element edges. The polygon model is piecewise constant, but allows polygons to have any number of vertices. In general, then, GIS provide no support for finite element modeling where the elements have uniformly three or four vertices, and variation is constant within an element.

Not all geographic phenomena are conveniently represented as fields, and the requirement that a field have a single value everywhere in the plane is often overly restrictive. Thus in addition to fields, GIS support the representation of phenomena as discrete objects—points, lines, or areas, which may overlap, and need not fill the plane. These *entity* models reflect an entirely different view of the world as composed of discrete objects with internally homogeneous characteristics, and one that is perhaps much closer to the ways people learn about the world and navigate within it (Mark & Frank, 1991). Entity models are common among GIS architectures that have been designed for facilities management applications, such as are found in highway departments, city engineering departments, or utility companies, where there are many examples of discrete entities, and almost none of spatially continuous fields. Some commercial GIS offer no capabilities at all for storing or manipulating fields. The field view seems generally more useful for scientific applications, and GIS that support them have been more widely adopted for environmental modeling.

## THE GEORELATIONAL MODEL

The basis for any digital representation of geographic phenomena is a collection of points, lines, and areas, though the rules governing collections of these primitive objects depend on whether the entity or field view is being implemented, and whether objects are planar enforced. In addition to primitive objects, any successful approach to geographic data modeling must allow for the representation of relationships between objects. Such relationships fall conveniently into three categories: those necessary to the successful representation of the objects themselves; those describing relationships evident from the objects' geometry; and those describing relationships of a more functional nature. The first category will not always be apparent to the user, because its examples may have been hidden by the system designer, but it includes the relationships between adjacent areas in a planar enforced layer of such areas, and the relationships between shared vertex points that define a TIN. The second includes the *lies in* relationship that assigns a point to its containing reporting zone, and the *overlaps* relationship that indicates whether the areas of two reporting zones intersect. Functions exist in most GIS to compute such relationships from the geometry of the primitive objects: The *lies in* relationship is computed with the *point-in-polygon* function, and *overlaps* with *polygon overlay*.

The *georelational model* emerged in the late 1970s as a specific implementation of the more general relational database model that offered distinct advantages for storing and manipulating spatial relationships. It is now the dominant architecture for GIS, though its dominance may be threatened in the next few years by more recent alternatives. Spatial objects are organized into classes sharing common characteristics, such as a class of drainage basins, or a class of point sample wells. Each class is conceptualized as a table, with the member objects forming the rows and the various attributes of each object as the columns.

This tabular model of data should be familiar from its use in the statistical packages and spreadsheets. In the georelational model, a relationship between two objects is represented as an additional attribute of one or sometimes both of them. For example, the *lies in* relationship would be represented as an additional column in the table of points, containing the identification number of the containing polygon, and thus *pointing* to its record in the relevant reporting zone table. There will be exactly one pointer because a point must lie in exactly one polygon, whereas the reverse, of pointing from polygons to points, would not be as simple. Simple operations on tables, such as counting points by polygon, are now easily carried out.

Besides relationships that can be determined from geometry, the georelational model also provides support for other kinds of relationships, such as those having to do with the processes occurring on the landscape and responsible for the patterns we see. One commonly implemented relationship in surficial hydrology applications of spatial databases is connectivity, allowing one link in the network to *point to* another link. Although connection can often be inferred from geometry, it is much more difficult to infer direction of flow, forcing the builders of such applications to treat each possible connection explicitly, or to make use of other information such as elevation.

## INTERACTIONS

Although pointers allow relationships to be defined between different types of objects, or between objects belonging to a single class, they provide no support for the qualification of relationships. For example, one might want to store the fact that a particular hydrologic connection between a sink and a spring was characterized by a certain flow-through time, or had a certain volume–head relationship. The georelational model allows us to do this by establishing a new table, or *relation*, with one entry per interaction. The columns of the table would include a pointer to the origin object, a pointer to the destination object, and various measures of interaction.

Unfortunately, at this point in time no available GIS provides comprehensive support for the representation of interaction. While relations such as that defined above exist in isolated instances, the necessary functions for basic manipulation of interaction data, such as display, or modeling of flows using standard spatial interaction models, are not provided by the majority of GIS vendors, and interaction modeling is only just beginning to appear as a supported function. Hopefully such functions will be much more common in the future.

The next section of the chapter reviews recent work in advanced data modeling, and its potential applications to subsurface modeling.

## ADVANCED GEOGRAPHIC DATA MODELING

Recent research has yielded a rich set of advanced techniques for geographic data modeling, particularly in areas such as time, linear networks, and hierarchies. The subsections of this part of the chapter review each of the major contributions, and outline ways in which they can be useful to studies of nonpoint-source pollution in the vadose zone.

## Hierarchical Structures

The traditional emphasis in geographic data modeling has been on the representation of a single level of generalization. Tools for automatic generalization, or the automatic production of one scale or spatial resolution of mapping from another, larger scale, have proven highly elusive (Buttenfield & McMaster, 1991), because of the difficulty of emulating in a machine the complex and sophisticated process used by the cartographer. Recently, however, significant advances have been made in the digital representation of hierarchy, or the logical linkage between data at different levels of spatial resolution.

One of the best known of these is the concept of the quadtree (Samet, 1990). Rather than model a single level of spatial resolution, a quadtree systematically decomposes a map into scales of variation, starting with the coarsest and proceeding to the most detailed. The basic quadtree concept has been implemented both as a method for representing fields, and as an index to the spatial objects in an entity database. In the latter case, the largest objects are associated with the coarsest spatial resolution. Advanced versions of this concept include more adaptable tree structures (von Oosterom, 1993; Kertesz et al., 1995) and wavelet decompositions (Chui, 1992).

Complex objects are another mechanism for modeling relationships between information at different spatial scales that is now widely supported among available GIS, particularly for facility management applications. Here, a feature represented by a single spatial object at one level of resolution may be linked to a set of more primitive features at another, more detailed level. This situation is commonly found in the systems of reporting zones used in hydrology, where detailed subwatersheds nest within coarse watersheds at several levels. Nested hierarchies such as this are common in geographical data, so it is surprising perhaps that so little support has been provided for them in traditional GIS designs. Support should include the ability to define relationships between objects at different scales, and simple functions such as aggregation and disaggregation. Recently, new techniques of exploratory spatial data analysis have allowed more than one level in a hierarchy to be viewed and analyzed simultaneously (Fotheringham & Rogerson, 1994), leading to useful insights into the effects of scale on the analysis of geographic data.

Although it is possible to model hierarchical relationships within a relational database, lack of supporting methods of manipulation and explicit techniques for representation have created the sense of a conflict between the georelational model as normally implemented in GIS, and the need to model hierarchical relationships. In the case of GDS, a GIS widely adopted within the facilities management industry, the central database architecture is hierarchical rather than georelational, indicating the importance attached to hierarchical spatial relationships in this application area, although links also exist to standard relational databases. Hopefully, new GIS products appearing on the market in the next few years will make the modeling of hierarchical relationships much easier. At this time, however, standard software products based on the georelational model offer only limited ability to explore the hierarchical dimension of data.

## Dynamic Segmentation

Road and river networks have provided a rich set of applications for GIS. In traditional geographic data modeling, networks are represented as connected sets of lines. Each line object points to other connected line objects, or to the nodes (a special class of points) at each end; in the latter case, the nodes in turn point to links. Link–node modeling of transport networks began in the 1960s with the Census Bureau's DIME project, and is currently generating widespread interest in the context of Intelligent Vehicle-Highway Systems (IVHS). Information about the distribution of phenomena along a network can be represented in the form of link and node attributes.

Although successful, the link–node model suffers from one major disadvantage: in reality, attributes are often not constant along links, and change in attributes is not confined to nodes. In principle, the network should be seen as a one-dimensional manifold embedded in a two-dimensional space; methods are needed for the systematic description of variation on this one-dimensional continuum that are analogous to the two-dimensional field and entity data models of GIS. On the one-dimensional manifold there are two entity models (line and point) and five field models (regularly and irregularly spaced sample points, planar enforced regular and irregular line segments, and segments characterized by linear change, the equivalent of a TIN; one could even imagine a one-dimensional equivalent of the isoline). Rather than introducing false nodes at every change of attributes, the *dynamic segmentation* model allows attributes to be assigned to points anywhere on the network, or to sections of links between points that can span intervening nodes. Although it does not implement all of the possible data models listed earlier, this advance on the traditional GIS data model has proven very useful in network applications wherever it is necessary to describe complex geographical variation over the geometry of a network. But as is often the case in GIS, its status as a work around solution to a practical problem works against its recognition as a theoretically distinct data type.

In hydrology, there is often a need to model not only the variation of phenomena along linear networks, such as surface channels, but also the interaction between such networks and the two- and three-dimensional fields of other surface and subsurface phenomena. In freshwater biology it may be necessary to switch between a linear view of a stream network, and a two- or three-dimensional view of the water body. Such transitions and transformations between different domains of geographic data modeling are common, and require an extensive set of appropriate geometric functions. Fortunately, the georelational model, with its system of pointers between objects, has provided a useful though not entirely comprehensive framework.

## Fuzzy Representations

In the traditional GIS data model all variation must be expressed through some combination of discrete, well-defined objects with precise *footprints* on the surface of the Earth. In a vector system, precision is determined by the arithmetic precision of the computer and its programming language, and can often be as high as one part in $10^{14}$. In raster-based systems positional precision is determined by cell size and is thus likely to be much coarser.

Despite the precision of vector-based systems, the positional accuracy of spatial objects is likely to be much less. Even the best surveying instruments achieve accuracies of only 1 part in $10^6$, and map digitizing can rarely exceed 1 part in $10^4$. Moreover, the definitions of many spatial objects fail to support even these levels of accuracy. A map of soils or land cover, for example, may include boundary lines between classes whose positions are definable to no better than 1 part in 100 (such as a boundary positioned to the nearest 100 m on a map covering an area 10 km wide). For this reason, there has been much interest recently in the modeling of uncertainty in spatial databases, and in studies of error and accuracy (Goodchild & Gopal, 1989). Fuzzy logic has been widely suggested as a framework for such models.

Many applications may require the merger of data sets with widely differing lineages and thus positional accuracies. To take one example, many boundaries of reporting zones run along rivers. To assign a point location to the correct reporting zone can require a high level of positional accuracy in both the data set containing the digitized river boundaries, and the data set containing the point locations.

Although traditional GIS data models made no accommodation for uncertainty, requiring the assumption that all object footprints were *crisp*, there has been much recent interest in explicit support for uncertainty, documentation of information on accuracy, and programs of accuracy assessment. Fear of legal liability is one of the major motivations behind this new interest. The recently adopted Federal spatial data format (Federal Information Processing Standard 173; Morrison, 1992) and metadata (Federal Geographic Data Committee Content Standards for Geospatial Metadata; see WWW home page http://fgdc.er.usgs.gov/metaover2.html) standards both contain guidelines for reporting and accessing information on quality. Other recent research has focused on techniques for communicating quality information to the user, through novel methods of visual display (Beard et al., 1991).

Other research effort has gone into methods of *error propagation*, which allow the effects of uncertainty in input data to be carried automatically into estimates of the uncertainty of the products of analysis (Heuvelink, 1993). Such methods may be useful in estimating the uncertainties associated with spatially-based policies in the area of agriculture or environmental health, and in dealing effectively with risk.

One of the greatest challenges in dealing effectively with the issues of uncertainty stems from the nature of maps, which frequently depend on complex patterns of measurement but rarely identify those measurements or their locations, or represent them in digital databases created from maps. For example, the measurements used to make soil or land cover maps are often scattered at point locations, the bulk of the information shown on the map having been interpolated from them. As a result, a large database of information items can depend on remarkably few actual measurements, leading to statistical problems stemming from vastly inflated numbers of degrees of freedom. In a spatial database, it is possible with a little ingenuity to preserve the original measurements as well as the interpolated data. But in general the current architecture of GIS and mapping tradition do little to discourage inappropriate statistical inferences.

## Temporal Change

Raw data collection in the field is costly, and traditional systems of data collection thus tend to emphasize those aspects of real systems that remain relatively constant through time, and to characterize change through the use of periodic *time slices*. This approach is reflected in the organization of the U.S. Department of Agriculture's Natural Resource Inventory (NRI), which samples the USA every 5 yr, and also in such remote sensing systems as Landsat, which takes a view of the surface of the Earth from space every 19 d. Maps also emphasize the comparatively static aspects of the Earth's surface, and these traditions have been preserved in the conventional GIS data models.

More recently, there has been substantial interest in introducing the temporal dimension to spatial databases, and in investigating whether traditional methods of data collection might not be usefully modified in response to the widespread use of digital data processing. Is it possible to rethink the time slice approach to data collection in the age of GIS?

Langran (1992) and Peuquet (1994) provide recent reviews of the state of temporal data modeling in GIS. One commonly encountered problem is the instability of reporting zone boundaries through time, which creates problems for any kind of longitudinal data analysis. Even though longitudinal stability is a stated objective of many systems of reporting zones, changes nevertheless occur in boundaries. One possibility is to maintain a master file of all boundary segments that ever existed, and to incorporate a GIS function that can rebuild from them the exact geometry of reporting zones that was valid at any specific time. This approach could be used, for example, to build the county boundary network of the USA at any time since Independence.

In other applications, it may be necessary to represent the space-time continuum as a three-dimensional or even four-dimensional raster, in order to support models of space-time processes. In such cases the time steps of a model can be equated to the layers of a GIS, and simulation reduced to a series of computations of state at time $t + 1$ from state at time $t$. The initial state at time 0 is similarly a layer. While this is feasible, many authors have commented on its essential inefficiency when implemented in standard GIS products. First, the command or scripting language of the GIS is unlikely to support functions related to time. van Deursen (1995) has recently devised and implemented a dynamic modeling language for GIS that deals effectively with this problem. Second, and more importantly, the architecture of the GIS will probably require each layer to be computed and stored before the next is computed. General-purpose codes for dynamic modeling on a raster, such as cellular automata codes, tend to adopt a different, more efficient approach, and to perform better on these simulation tasks as a result.

### Three Dimensions

Systematic modeling of the vadose zone requires a three-dimensional approach. Just as in two dimensions, representation of three-dimensional phenomena can make use of field and entity representations, but the set of primitive objects must be extended to include volumes, whether as polyhedra (the equivalent of polygons) or as voxels (three-dimensional pixels). The quadtree also has been extended to three dimensions as the *octree*.

Several issues arise in handling volumetric data. First, the structure of GIS is two-dimensional, and volumetric data must be integrated through linkages to specifically volumetric databases. Several GIS vendors offer linkages to volumetric packages. Second, three-dimensional data are voluminous, requiring attention to problems of database partitioning, access speed, and indexing in order to produce reasonably acceptable performance. Third, raw three-dimensional data are often expensive to collect, and there is no tradition of data publication comparable to the tradition of two-dimensional mapping. Finally, it is not clear that the functionality of two-dimensional GIS translates to a simple three-dimensional equivalent—if one had a three-dimensional GIS, what would one want to do with it?

## FUNCTIONALITY

While thinking about data modeling has progressed markedly in the past few years, much available GIS software remains structured along the lines established by the raster–vector cleavage. Although raster–vector conversion is supported, processing is structured around functions that expect and produce regular arrays, and functions that expect and produce combinations of discrete points, lines, and areas.

Two advances on this situation can be expected in the future. First, the raster–vector cleavage is inappropriate to a conceptual framework that distinguishes between field and entity models, since a field can be represented in six ways, two of which are raster-like and four vector-like. Kemp (1993) has discussed the design of a level of user interaction that would focus on the user's concept of field, and hide lower level issues of field representation as far as possible. For example, the user need not be aware of the details of the representation of what is conceived as a continuous surface of terrain elevation, or water table, and can compute such properties as slope without interacting at a lower level with the primitive objects used to create the slope representation. Of course interaction is necessary for some functions, particularly those having to do with accuracy of representation.

Second, if the level of user interaction can be raised to the level of the entity–field cleavage, then integration of the respective functions becomes much easier. It should be possible, for example, to query a field representation for the average value within an area entity, or to project a field representation of elevation onto a one-dimensional river network. In current architectures, the user would need to know the representation details in order to select the appropriate series of commands.

In hydrologic applications, it may be useful to make a formal distinction between three classes of information, specifically entities (points, lines, or areas), two-dimensional fields, and fields on networks (one-dimensional fields embedded in a two-dimensional space). The benefits of this conceptual reorganization become especially apparent in relation to the functions that link data of the three types. Consider, for example, the task of modeling overland sheet flow as a two-dimensional field, and accumulating it as a one-dimensional field over a surface network. In a three-dimensional extension, consider the functions needed to handle surface entity representations of underground planes of discontinuity and their interaction with three-dimensional field representations of fluid flow.

The ability to transform a set of sample point observations to a representation of an estimated continuous field is one of the more important in environmental modeling of all kinds, and the vadose zone is no exception. Spatial interpolation is necessary when transforming from one field data model to another, particularly in order to integrate two data sets with disparate data models. It occurs in resampling, contouring, and other more complex operations.

The techniques of geostatistics have become among the most popular of spatial interpolation methods, in part because they are solidly grounded in statistical theory. Although integration of geostatistical software with GIS has been slow in the past, most GIS packages widely used in environmental modeling offer at least simple Kriging, and there is growing awareness in the GIS application community of the importance of related techniques such as conditional simulation (Englund, 1993). The GRASS GIS environment (for information see the WWW home page at http://www.cecer.army.mil/grass/GRASS.main.html) has proven particularly suitable for rapid prototyping of new functions to support environmental modeling of all kinds.

## CONCLUSIONS

The focus of this chapter has been on the nature of geographic data modeling in two contexts. Traditional GIS data models have emphasized the representation of the contents of maps, and thus have modeled real geographic phenomena as layers of fixed, crisply defined points, lines, and areas. The advanced data models that have emerged in the past decade, largely in response to the inadequacies of the earlier generation, have dealt explicitly with time, three dimensions, fuzziness, hierarchical relationships across scales, interactions, and complex patterns on networks. These new ideas have only just begun to influence practice, and their full influence is yet to be seen. The GIS field is conservative in such matters, and it can be difficult for products offering new ideas in data modeling to break into a market dominated by a few large vendors. This chapter also has made suggestions about areas where the newer more advanced data models are likely to influence practice in non-point-source pollution modeling in the vadose zone.

There has not been space in this chapter to discuss several important trends in advanced data modeling. The chapter has followed traditional practice in separating the issues of representation from the functions to be performed on the data, and this tradition is now under regular and strong attack from supporters of *object orientation*, who argue that by *encapsulating* functions with data it will be possible to escape many of the limitations currently imposed by choice of data model. For example, if a set of irregularly spaced point observations of depth to water table could be packaged with a function for spatial interpolation, then it would be possible for the user to ignore the particular representation, and to think of the data simply as a field. This kind of approach holds the promise of much greater ease in transferring data from one system to another, and of *interoperability* between systems. At the same time, the rigid concepts of discrete objects that underlie object orientation seem at times to be less than fully compatible with spatially continuous concepts of fields, and associated ideas of geographic seamlessness and fuzziness.

With a steadily increasing number of options for geographic data modeling available, it seems likely that *niche* implementations of GIS will appear, offering the subset of data modeling options found to be most useful in some specific application area. Dynamic segmentation is more likely to be supported by vendors competing in the market for hydrologic applications, while clearly of less interest for other areas of resource management. At this stage it is not clear whether the needs of vadose zone modeling are sufficiently well defined to provide a niche, or whether the broader needs of hydrology are sufficient to justify a GIS for hydrologists.

Geographic data models provide the underlying architectural structure of GIS, and of its interaction with data generated by other geographic information technologies, such as remote sensing. The specific problems of integrating GIS and remote sensing from the perspective of geographic data models are discussed by Goodchild (1994). This chapter has presented a brief review of the current state of geographic data modeling, and of recent research that has attempted to go beyond conventional data models. This research promises specific benefits to environmental impact assessment, and vadose zone modeling in particular, because of its emphasis on time and three dimensions, hierarchical relationships, and the modeling of variation over linear networks.

Because of its reliance on the raster–vector cleavage, the current range of GIS products handles these more advanced concepts of geographic data modeling through a variety of work arounds, rather than by implementation within the architecture. With a stronger theoretical base and a better series of linkages to the ways scientists think about spatial variation, much of the technical complexity of GIS might be shown to be unnecessary.

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