1.4 GEOGRAPHIC INFORMATION SYSTEMS AND ENVIRONMENTAL MODELING

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1. INTRODUCTION

In its broadest sense, the term 'Geographic Information System' refers to any digital information system whose records are somehow geographically referenced. However this very general definition conveys little sense of the nature of a GIS, or of its applications. In terms of its functions, a GIS is a system for input, storage, analysis and output of geographical data, and it is generally accepted that of those, analysis is the most important. Very generally, a GIS may be described as a system for support of geographically based decisions, or a 'Spatial Decision Support System' (Cowen 1988). GIS finds uses in management of geographically distributed facilities, analysis and modeling of geographical data, manipulation of information for making maps, and management of natural resources. Numerous survey texts provide overviews (for a broad overview of GIS see Bylinski 1989: for texts see Star and Estes 1990; Burrough 1986; Aronoff 1989) and general coverage can be found in the magazine *GIS World*.

Like any information system, a GIS combines a database with a set of procedures or algorithms that operate on the database. Because of the geographical nature of the data, the input and output subsystems must be unusually elaborate, and must rely on specialized graphics hardware such as plotters, digitizers and scanners. Historically, the development of GIS has been to some extent constrained by the availability of suitable specialized hardware. At the same time the database itself must be structured to handle the complications of geographical data. Data modeling, or the process by which the real world is measured and captured in discrete database records, is particularly difficult for geographical data and has been the subject of much research and development effort. Finally, the design of efficient algorithms for standard geographical operations has also proven to be a major challenge, exacerbated by the very large volume of much geographical data, particularly imagery.

GIS has often been seen as a valuable tool for scientific research - as an 'enabling technology' for a wide range of disciplines (for example see Zubrow, Allen and Green 1990 for a discussion of GIS applications in archaeology). We use the term 'spatial analysis' to describe a set of techniques for analyzing geographic data - techniques whose results are not invariant under changes in the locations of the observations being analyzed. Under this definition many models and techniques of analysis are not spatial - changes in the locations of observations will not normally affect the outcome of a regression analysis. Thus while the statistical packages (e.g. S, SPSS, SAS) exist to support a wide range of statistical analyses, GIS can be seen as existing to support spatial analysis. Abler (1987) has expressed this point very strongly in relation to geographical analysis: "GIS are simultaneously the telescope, the microscope, the computer, and the xerox machine of regional analysis and synthesis." In essence, a GIS provides a geographical perspective on information. Just as a graph of two variables can suggest a causal linkage, maps showing the geographic locations of phenomena can also be very powerful tools for developing insight and explanation, in addition to their value in organizing information.

The GIS industry is currently enjoying a period of dramatic expansion, and growth rates of over 20% are often reported (Rhind 1990). However it is clear that the reason for much of this growth has little to do with the application of GIS as a scientific tool, or to environmental modeling in particular. While numerous universities have developed GIS courses (Morgan 1987) and invested in GIS hardware and software, sales to governments, utilities, the military and resource-based corporations for information management vastly exceed sales for scientific research. In recent years much development effort in the GIS software industry has gone into information management-related capabilities, and relatively little into spatial analysis and modeling.

The purpose of this paper is to offer a series of reflections on the current state of GIS applications in environmental modeling. It looks in detail at the assumptions that would lie behind an enthusiastic endorsement of GIS. The first section discusses the vital issue of data modeling, compares current GIS data models, and asks whether current thinking on GIS data models can inform the modeling of environmental processes. The second section looks at GIS functionality, and at the functional requirements of environmental modeling, and asks what functions GIS should be expected to perform in this set of applications. The third and final section examines the state of GIS research, and its relationship to the perceived needs of environmental science.

2. GIS DATA MODELS

2.1 Standard models

Many geographical distributions, such as those of soil variables, are inherently complex, revealing more information at higher spatial resolution apparently without limit (Mandelbrot 1982). Because a computer database is a finite, discrete store, it is necessary to sample, abstract, generalize or otherwise compress information. 'Geographical data modeling' is the process of discretization that converts complex geographical reality into a finite number of database records or 'objects'. Objects have geographical expression as points, lines or areas, and also possess descriptive attributes. For example, the process of sampling weather-related geographic variables such as atmospheric pressure at weather stations creates point objects and associated measured attributes.

GIS technology recognizes two distinct modeling problems, depending on the nature of the distributions being captured. When the distributions in reality are spatially continuous functions or 'fields', such as atmospheric pressure or soil class, the database objects are creations of the data modeling process. The set of objects representing the variation of a single variable are termed a 'layer', and the associated models are 'layer models'. However there are numerous instances where the database objects are defined a priori, rather than as part of the modeling process. The object 'Lake Ontario' is meaningful in itself, and has an identity that is independent of any discretization of a binary water/land variable over North America. We refer to these as 'object models'. In a layer model every location by definition has a single value of the relevant variable, whereas in the object model there would be no particular problem in allowing a location to be simultaneously occupied by more than one object. For example the 'Bay of Quinte' is also in 'Lake Ontario'. The term 'planar enforcement' is often used to reflect the fact that objects in a layer model may not overlap; planar enforcement clearly is not relevant to the object models.

A major difficulty arises in the case of the object models when a well-defined object has no equally well-defined location. For example, the spatial extent of Lake Ontario would most likely be defined by some notion of average elevation, but this is not helpful in deciding when Lake Ontario ends and the St Lawrence River begins. Many geographical objects have inherently fuzzy spatial extents. One common solution to this problem is to allow objects to have 'multiple representations' - spatial extents that vary with scale. A river, for example, might be a single line at scales smaller than 1:50,000, but a double line at larger scales. Both geometric and topological expression vary in this case as the object changes from line to area.

2.2 The layer models

The purpose of layer models is to represent the spatial variation of a single variable using a collection of discrete objects. A spatial database may contain many layers, each able in principle to return the value of one variable at any location (x,y) in response to a query. Because information is lost in modeling, the value returned may not agree with observation or with the result of a ground check, so accuracy is an important criterion in choosing between alternative data models. We define the accuracy of a layer as $E(z - z')^2$ where z is the true value of the variable, as determined by ground check, and z' is its estimated value returned from the database. Note that z may be inherently uncertain because of definition or repeated measurement problems.

Six layer models are in common use in GIS:

1. Irregular point sampling: the database contains a set of tuples <x,y,z> representing sampled values of the variable at a finite set of irregularly spaced locations (e.g. weather station data).
2. Regular point sampling: as (1) but with points regularly arrayed, normally on a square or rectangular grid (e.g. a Digital Elevation Model).
3. Contours: the database contains a set of lines, each consisting of an ordered set of <x,y> pairs, each line having an associated z value; the points in each set are assumed connected by straight lines (e.g. digitized contour data).
4. Polygons: the area is partitioned into a set of polygons, such that every location falls into exactly one polygon; each polygon has a value which is assumed to be that of the variable for all locations within the polygon; boundaries of polygons are described as ordered sets of <x,y> pairs (e.g. the soil map).
5. Cell grid: the area is partitioned into regular grid cells; the value attached to every cell is assumed to be the value of the variable for all locations within the cell (e.g. remotely sensed imagery).
6. Triangular net: the area is partitioned into irregular triangles; the value of the variable is specified at each triangle vertex, and assumed to vary linearly over the triangle (e.g. the Triangulated Irregular Network or TIN model of elevation).

Other possibilities, such as the triangular net (6) with non-linear variation within triangles (Akima 1978), have not received much attention in GIS to date.

Each of the six models can be visualized as generating a set of points, lines or areas in the database. Models (2) and (5) are commonly called 'raster' models, and (1), (3), (4) and (6) are 'vector' models (Peuquet 1984); storage structures for vector models must include coordinates, but in raster models locations can be implied by the sequence of objects. Models (3) and (6) are valid only for variables measured on continuous scales.

Models (4), (5) and (6) explicitly define the value of the variable at any location within the area covered. However this is not true of models (1), (2) and (3), which must be supplemented by some method of spatial interpolation before they can be used to respond to a general query about the value of z at some arbitrary location. For example, this is commonly done in the case of continuous-scaled variables in model (2) by fitting a plane to a small 2x2 or 3x3 neighborhood. However this need for a spatial interpolation procedure tends to confound attempts to generalize about the value of models (1), (2) and (3).

In practice, model (6) is reserved for elevation data, where its linear facets and breaks of slope along triangle edges fit well with many naturally occurring topographies (Mark 1979). It would make little sense as a means of representing other variables, such as atmospheric pressure, since curvature is either zero (within triangles) or undefined (on triangle edges) in the model. Models (2) and (4) are frequently confused in practice, since the distinction between point samples and area averages is often unimportant.

Models (1) and (3) are commonly encountered because of the use of point sampling in data collection and the abundance of maps showing contours respectively, but are most often converted to models (2), (4), (5) or (6) for storage and analysis. The ability to convert between data models, using various algorithms, is a key requirement of GIS functionality.

2.3 The object models

Objects are modeled as points, lines or areas, and many implementations make no distinction in the database between object and layer models. Thus a set of lines may represent contours (layer model) or roads (object model), both consisting of ordered sets of <x,y> pairs and associated attributes, although the implications of intersection, for example, are very different in the two cases.

Object models are commonly used to represent man-made facilities. An underground pipe, for example, is more naturally represented as a linear object than as a value in a layer. Pipes can cross eachother in object models, whereas this would cause problems in a layer model. Most man-made facilities are well-defined, so the problems of fuzziness noted earlier are likely not important. Another common use of object models is in capturing features from maps.

Object models are also commonly used to capture aspects of human experience. The concept 'downtown' may be very important in building a database for vehicle routing or navigation, forcing the database designer to confront the issue of its representation as a geographical object. In an environmental context, McGranaghan (1989a,b) has shown how this issue is important in handling the geographical referrents used in herbarium records.

Finally, object models can be conceptualized as the outcome of simple scientific categorization. The piecewise approximation inherent in layer model (4) assigns locations to a set of discrete regions, in the geographical equivalent of the process of classification. In geomorphology, the first step in building an understanding of the processes that formed a given landscape is often the identification of 'landforms' or 'features', such as 'cirque' or 'drumlin'. Band (1986), among others, has devised algorithms for detecting such objects from other data. Mark (1989) has discussed the importance of categories in the GIS context, and there is growing interest in understanding the process of object definition and its effects. For most purposes, environmental data modeling is dominated by the layer view, and its concept of spatially continuous variables. But the object view is clearly important, particularly in interpreting and reasoning about geographical distributions.

2.4 Network models

Both layer and object models have been presented here as models of two-dimensional variation. An important class of geographic information describes continuous variation over the one-dimensional space of a network embedded in two-dimensional space. For example, elevation, flow, width and other parameters vary continuously over a river network, and are not well represented as homogeneous attributes of reaches. Models (1), (2), (4), (5) and (6) can all be implemented in one-dimensional versions, but none are supported in this form in any current GIS.

2.5 Choosing data models

In principle, the choice of data model should be driven by an understanding of the phenomenon itself. For example, a TIN model will be an appropriate choice for representing topography if the earth's surface is accurately modeled by planar facets. Unfortunately other priorities also affect the choice of model. The process of data collection often imposes a discretization, the photographic image being a notable exception. The limitations of the database technology may impose a data model, as for example when a 'raster' GIS is used and the choices are therefore reduced to layer models (2) and (4), or when a 'vector' GIS is used and a cell grid must be represented as polygons. Finally convention can also be important, particularly in the use of certain data models to show geographic variation on maps. For example, digitized contours are used in spatial databases not because of any particular efficiency - in fact accuracy in a layer sense is particularly poor - but because of convention in topographic map-making.

2.6 Relationships

A digital store populated by spatial objects - points, lines and areas - would allow the user to display, edit or move objects, much as a computer-aided design (CAD) system. However spatial analysis relies heavily on interactions between objects, of three main forms:

- relationships between simple objects, used to define more complex objects (e.g. the relationships between the points forming a line);
- relationships between objects defined by their geometry (e.g. containment, adjacency, connectedness, proximity); and
- other relationships used in modeling and analysis.

Examples of the third category of relationships not determined by geometry alone include 'is upstream of' (connectedness would not be sufficient to establish direction of flow, and a sink and a spring may not be connected by any database object). In general, a variety of forms of interaction may exist between the objects in the database. In order to model these, it is important that the database implement the concept of an 'object pair', a virtual object which may have no geographical expression but may nevertheless have attributes such as distance, or volume of flow.

2.7 Recent trends in data modeling

Recently there has been much discussion in the GIS community over the value of 'object orientation', a generic term for a set of concepts that have emerged from theoretical computer science (see for example Egenhofer and Frank 1988a,b). Unfortunately the debate has been confused by the established usages of 'object' in GIS, both in the sense of 'spatial object' as a point, line or area entity in a database, and also 'object model' as defined here.

Three concepts seem particularly relevant. 'Identity' refers to the notion that an object can possess identity that is largely independent of its instantaneous expression, with obvious relevance to the independence of object identity and geographic expression in GIS. 'Encapsulation' refers to the notion that the operations that are possible on an object should be packaged with the object itself in the database, rather than stored or implemented independently. Finally, 'inheritance' refers to the notion that an object can inherit properties of its parents, or perhaps its component parts. As a geographical example, the object 'airport' should have access to its component objects - runway, hangar, terminal - each of which is a spatial object in its own right.

Of the three concepts, inheritance seems the most clearly relevant, particularly in the context of complex objects, and in tracking the lineage of empirical data. It seems increasingly important in the litigious environment which surrounds many GIS applications to track the origins and quality of every data item.

Encapsulation seems to present the greatest problems for modeling using GIS. In a modeling context, the operations that are permissible on an object are defined by the model, and are therefore not necessarily treatable as independent attributes of the object. This issue seems particularly important in the context of the discussion of object orientation in location/allocation modeling by Armstrong, Densham and Bennett (1989). For example, one can rewrite the shortest path problem by treating each node in the network as a local processor, making it possible to encapsulate the operations of a node with the object itself. It is possible that this process of rewriting may lead to useful insights in other models as well.

A related debate is that over procedural and declarative languages: a user should be able to declare 'what' is required (declarative), and not have to specify 'how' it should be done (procedural). But are these largely distinguishable in a modeling context, and do they imply that the modeler should somehow surrender control of the modeling process to the programmer?

The role of data models in environmental analysis and modeling is clearly complex. Models written in continuous space, using differential equations, are independent of discretization. But for all practical purposes modeling requires the use of one or more of the data models described here. Perhaps the greatest advantage of GIS is its ability to handle multiple models, and to convert data between them.

3. FUNCTIONALITY FOR ENVIRONMENTAL MODELING

The statistical packages are integrated software systems for performing a wide variety of forms of analysis on data. By analogy, we might expect GIS to integrate all reasonable forms of spatial analysis. However this has not yet happened, for several reasons. First, while the analogy between the two systems may be valid, there are important differences. The statistical packages support only one basic data model - the table - with one class of records, whereas GIS must support a variety of models with many classes of objects and relationships between them. Much of the functionality of GIS must therefore be devoted to supporting basic housekeeping and transformation functions that would be trivial in the statistical packages.

Second, spatial databases tend to be large, and difficult and expensive to create. While many users of statistical packages input data directly from the keyboard, it is virtually impossible to do anything useful with a GIS without devoting major effort to database construction. Recently there have been significant improvements in this situation, with the development of improved scanner and editing technology.

Third, while there is a strong consensus on the basic elements of statistical analysis, the same is not as true of spatial analysis. The literature contains an enormous range of techniques (for examples see Serra 1982; Unwin 1981; Upton and Fingleton 1985), few of which could be regarded as standard.

Because of these issues and the diversity of data models, GIS has developed as a loose consortium, with little standardization. While ESRI's ARC/INFO and TYDAC's SPANS are among the most developed of the analytically-oriented packages, they represent very different approaches and architectures. Among the most essential features to support environmental modeling are:

- support for efficient methods of data input, including import from other digital systems;
- support for alternative data models, particularly layer models, and conversions between them using effective methods of spatial interpolation;
- ability to compute relationships between objects based on geometry (e.g. intersection, inclusion, adjacency), and to handle attributes of pairs of objects;
- ability to carry out a range of standard geometric operations, e.g. calculate area, perimeter length;
- ability to generate new objects on request, including objects created by simple geometric rules from existing objects, e.g. Voronoi polygons from points, buffer zones from lines;
- ability to assign new attributes to objects based on existing attributes and complex arithmetic and logical rules;
- support for transfer of data to and from analytic and modeling packages, e.g. statistical packages, simulation packages.

Because of the enormous range of possible forms of spatial analysis, it is clearly absurd to conceive of a GIS as a system to integrate all techniques, in contrast to the statistical packages. The last requirement above proposes that GIS should handle only the basic data input, transformation, management and manipulation functions, leaving more specific and complex modeling to loosely coupled packages. Whereas the statistical packages are viable because they present all statistical techniques in one consistent, readily accessible format, GIS is viable for environmental modeling because it provides the underlying support for handling geographical data, and the 'hooks' needed to move data to and from modeling packages.

4. GIS RESEARCH

The current range of GIS software and hardware products incorporates an impressive range of technological breakthroughs. Concepts such as the TIN and quadtree (Samet 1989) are the direct result of GIS research, and are only two among the many innovative ideas to have emerged over the past three decades. Any technologically based field must be constantly supplied with new ideas if it is to thrive, and needs to be supported by an active research and development community.

However there is a strong feeling at the present time in the GIS community that the most important issues confronting the field are not necessarily technological. The GIS community seems to be converging not around a single, uniform software product (a standard GIS) or a single application, or around the technology itself, but around a set of generic issues that emerge from the technology. Whatever the application or EDP solution, every user of GIS faces the same set of problems in dealing effectively with digital geographic data, and these problems in turn form the agenda for discussion at GIS meetings - the true glue of the GIS community. Some of the more prominent are:

- data capture - how to convert data from raw to digital form in an efficient, cost-effective manner;
- data modeling - how to represent the infinite complexity of the real world in a discrete, digital machine - whether to use raster or vector, layers or objects, how to model complex objects;
- accuracy - how to cope with the uncertainty present to varying degrees in all geographical data;
- volume - how to deal with the fact that demands for geographical data will often exceed the space available for storage;
- access - how to design data structures, indexes and algorithms to provide rapid access to large volumes of geographic data;
- analysis - how to link GIS databases with advanced modeling capabilities;
- user interfaces - how to present the GIS database to the user in a friendly, comprehensible, readily used fashion;
- costs and benefits - how to measure the benefits of GIS information and compare them to the costs;
- impact on organizations - how to introduce GIS successfully into a complex organization.

All of these issues transcend the technology itself, and all of them in one way or another affect the technology's usefulness, whatever the application and whatever the platform. In recent years they have emerged in various guises as the basis of the research agendas of the NCGIA (NCGIA 1989), URISA (Craig 1989) and the UK Regional Research Laboratories (Masser 1990; Maguire 1990). Goodchild (1990) has argued that together they constitute a science of geographic information, and that the future of the GIS community lies in recognizing a common interest in geographic information science rather than the technology of geographic information systems.

The case for GIS as a science of geographic information will likely be debated for many years to come, but the complementary argument that GIS is a technological tool for the support of science is much more widely accepted, and reflected in applications from archaeology to epidemiology. Geography provides a very powerful way of organizing and exploring data, but the map has lagged far behind the table and graph because early generations of scientific computing tools made it so difficult to handle. GIS has finally provided the breakthrough, although it remains far from perfect. If we were to draw an analogy between GIS and statistical software, which began to emerge in the 1960s, then the current state of GIS development is probably equivalent to the state of the statistical packages around 1970. But GIS and statistics are ultimately very complementary sets of tools, both capable of supporting an enormous range of scientific inquiry.

To date, the major success of GIS has been in capturing and inventorying the features of the earth's surface, particularly as represented on maps, and in supporting simple queries. There has been much less success in making effective use of GIS's capabilities for more sophisticated analysis and modeling. It is hard to find examples of insights gained through the use of GIS, or discoveries made about the real world. GIS has not yet found widespread application in the solution of major social problems - disaster management, environmental quality, global issues or health. In part this comment is unfair, because such insights would be next to impossible to document. In part the reason is commercial - the market for GIS as an information management tool is far larger than that for spatial analysis, and vendors have invested relatively little in developing and promoting analytic and modeling capabilities. And although GIS is a major improvement, it is still difficult to collect, display and analyze data in geographical perspective. Finally, Couclelis (1989) has made the point that the current generation of GIS concentrates on a static view of a space occupied by passive objects, and offers little in support of the analysis of dynamic interactions.

5. CONCLUSIONS

GIS is a rapidly developing technology for handling, analyzing and modeling geographic information. To those sciences that deal with geographic information it offers an integrated approach to data handling problems, which are often severe. The needs of environmental modeling are best handled not by integrating all forms of geographic analysis into one GIS package, but by providing appropriate linkages and hooks to allow software components to act in a federation.

In addition to the technology, the GIS research community is increasingly concerned with the generic issues that surround digital geographic data. While these are in many cases old issues, the digital environment forces the analyst to confront them explicitly. Research now emerging from the GIS community on such issues as data accuracy and data modeling should be of widespread value to environmental science.

6. REFERENCES

Abler, R.F. (1988) Awards, rewards and excellence: keeping Geography alive and well. *Professional Geographer* 40(2), 135.

Akima, H. (1974) A method of bivariate interpolation and smooth surface fitting for irregularly spaced data points. Algorithm 526. *ACM Transactions on Mathematical Software* 4, 148.

Armstrong, M.P., Densham, P.J. and Bennett, D.A. (1989) Object oriented locational analysis. *Proceedings, GIS/LIS '89* Bethesda, MD, ASPRS/ACSM, 717.

Aronoff, S. (1989) *Geographic Information Systems: A Management Perspective*. WDL, Ottawa.

Band, L.E. (1986) Topographic partition of watersheds with digital elevation data. *Water Resources Research* 22, 15.

Burrough, P.A. (1986) *Principles of Geographical Information Systems for Land Resources Assessment*. Clarendon, Oxford.

Bylinski, G. (1989) Managing with electronic maps. *Fortune* (April 24), 237.

Couclelis, H. (1989) Geographically informed planning: requirements for a planning-relevant GIS. Presented to the North American meetings of the Regional Science Association, Santa Barbara, November.

Cowen, D.J. (1988) GIS versus CAD versus DBMS: what are the differences? *Photogrammetric Engineering and Remote Sensing* 54, 1551.

Craig, W.J. (1989) URISA's research agenda and the NCGIA. *Journal of the Urban and Regional Information Systems Association* 1(1), 7.

Egenhofer, M.J. and Frank, A.U. (1988a) Object-oriented databases: database requirements for GIS. *Proceedings, IGIS: The Research Agenda*. NASA, Washington DC, 2, 189.

Egenhofer, M.J. and Frank, A.U. (1988b) Designing object-oriented query languages for GIS: human interface aspects. *Proceedings, Third International Symposium on Spatial Data Handling*, 79.

Goodchild, M.F. (1990) Keynote address: spatial information science. *Proceedings, Fourth International Symposium on Spatial Data Handling, Zurich*, 1, 3.

Maguire, D.J. (1990) A research plan for GIS in the 1990s. In: Foster, M.J. and Shand, P.J. (eds.) *The Association for Geographic Information Yearbook 1990*. Taylor and Francis, London, 267.

Mandelbrot, B.B. (1982) *The Fractal Geometry of Nature*. Freeman, San Francisco.

Mark, D.M. (1979) Phenomenon-based data structuring and digital terrain modeling. *GeoProcessing* 1, 27.

Mark, D.M. (1989) Cognitive image-schemata for geographic information: relation to user views and GIS interfaces. *Proceedings, GIS/LIS '89* ASPRS/ACSM, Bethesda, MD, 551.

Masser, I. (1990) The Regional Research Laboratory initiative: an update. In: Foster, M.J. and Shand, P.J. (eds.) *The Association for Geographic Information Yearbook 1990*. Taylor and Francis, London, 259.

McGranaghan, M. (1989a) Incorporating bio-localities in a GIS. *Proceedings, GIS/LIS '89*. ASPRS/ACSM, Bethesda, MD.

McGranaghan, M. (1989b) Context-free recursive-descent parsing of location-descriptive text. *Proceedings, AutoCarto 9* ASPRS/ACSM, Bethesda, MD, 580.

Morgan, J.M. (1987) Academic geographic information systems education: a commentary. *Photogrammetric Engineering and Remote Sensing* 53, 1443.

NCGIA (1989) The research plan of the National Center, for Geographic Information and Analysis. *International Journal of Geographical Information Systems* 3(2), 117.

Peuquet, D.J. (1984) A conceptual framework and comparison of spatial data models. *Cartographica* 21(4), 66.

Samet, H. (1989) *Design and Analysis of Spatial Data Structures*. Addison-Wesley, Reading, MA.

Serra, J.P. (1982) *Image Analysis and Mathematical Morphology*. Academic Press, New York.

Star, J.L. and Estes, J.E. (1990) *An Introduction to Geographic Information Systems*. Prentice-Hall, Englewood Cliffs, NJ.

Unwin, D.J. (1981) *Introductory Spatial Analysis*. Methuen, New York.

Upton, G.J.G. and Fingleton, B. (1985) *Spatial Data Analysis by Example*. Wiley, New York

Zubrow, E., Allen, K. and Green, S. (1990) *Interpreting Space: GIS in Archaeology and Anthropology*. Taylor and Francis, London.