GEOINFORMATICS

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Summary

This Theme-level writing on Geoinformatics summarizes the Topics and Articles found within this Theme. The Theme focuses on the four Topics of (i) Sample Data and Survey, (ii) Remote Sensing, (iii) Statistical Analysis in the Geosciences and (iv) International Cooperation for Data Acquisition and Use. While a wide range of topics encompassed by the broad theme of geoinformatics is included, the emphasis is on remote sensing as a primary data source with which to tackle the regional-to-global scale issues that face humankind. In this Theme-level writing, geoinformatics is introduced and the fundamentals of geographical data handling are described (including sampling theory). Remote sensing principles are explained and some hypothetical examples are used to illustrate modelling in remote sensing. The field of geographical information systems (GIS) is introduced, including distinction between the raster and vector data models and an explanation of the overlay operation. The discussion is extended to spatial statistical modelling, including geostatistics. Finally, the Theme closes with a brief discussion of international cooperation and its role in facilitating geoinformatics applied at the global scale.

1. Introduction

For many years, astronomers held an anthropocentric view of the Universe. In 1514 (published in 1543) Copernicus put forward a theory that the Earth revolves around the Sun (not *vice versa*), and so began a humbling journey for humankind that was to reveal, increasingly, the apparent insignificance of the Earth and our Solar System in an immense Universe.

Very recently, competing theories have tried to explain how a small planet close to the Sun (i.e., Earth) could have a satellite as large as our moon (approximately 1/3 of the Earth's mass). In the Universe, this is believed to be rare. The most plausible theory is that by chance a large lump of rock (a planetesimal) collided with the Earth early in its genesis vaporising a massive surface layer from the Earth to form the moon. Importantly, the consequence is that the conditions (large satellite orbiting a planet close to a star) found on Earth are much more likely to be rare in the Universe than previously thought.

Against the above description of the rarity of our world in an immense Universe, one may consider the effect that humankind has had on our environment. One has only to think of the vastness of any one of hundreds of large cities to realise the huge impact that humans have had on the Earth's land cover. If you have flown into a major city you will be all too aware of the scale of urbanisation that has taken place over the last few hundred years. In fact, we seem to have changed almost every corner of our environment in some way; most often directly, but at least indirectly. Rivers, watercourses, lakes and the oceans are affected. Soils, biological systems and fragile ecosystems are changed irrevocably. Atmospheric constituents such as CO_2 and ozone are changing in quantity. The time lags in such a huge system mean that even if we stopped our influence today, the system would not stabilise for perhaps hundreds of years. If one takes the time to sit back and really look at what we have done, and are still doing, to our environment, particularly since the industrial revolution, the picture is all too clearly one of exploitation of resource above sustainability of life support systems.

To be fair, our predecessors were partially ignorant of their effect on the environment. Humankind, in general, has only recently (1960s) seen pictures sent back from the Apollo spacecraft in which the Earth is unambiguously a globe, a planet amongst others in the solar system. These pictures have surely brought about a subtle, but massive, change in consciousness in that we are now truly aware of the fragility of our world. A multitude of environmental initiatives have been set up to counter our unchecked exploitation of our limited environment. However, unlike our ancestors, we are in receipt of much greater knowledge and understanding about human impact on the environment. It is surprising, therefore, that we do not, as a species, do more. One reason for the limited scale of individual endeavours in the name of "protecting" or "helping" the environment is surely humankind's innate inability to act as one, always needing to protect one individual's or group's (e.g., nation's) interests relative to another's. A second reason is humankind's inability to put a market price on environmental values (particularly in a free-market economy). Whatever the reason, it is clear that environmental awareness and initiatives are increasing, and it is in this context that this Encyclopaedia is placed. It is hoped that this Theme will contribute in a small way to the overall objectives of this Encyclopaedia, in providing knowledge, tools and understanding with which to create sustainable life support systems.

1.1. Geoinformatics

Geoinformatics has many different possible meanings and interpretations. In this Theme, Geoinformatics is taken to be a set of tools for the acquisition, analysis and presentation of spatial data relating to properties on the surface of the Earth. In the context of Life Support Systems this toolkit can be seen as a decision-support system and this definition is explored in this Theme. Geoinformatics is usually thought to comprise several distinct toolkits including geophysics, geotechnics, navigation, surveying, global positioning systems (GPS), photogrammetry, remote sensing, geographical information systems (GIS), geostatistics and geoComputation. While all of these components are included implicitly in this Theme, the treatment is biased in favour of remote sensing, GIS and spatial (geo) statistics. The reason is that in the view of this author, in the context of life support systems at the *global scale*, remote sensing and subsequent analysis of the data provided have a key rôle to play (see further discussion below). The structure and content of this Theme reflect that belief.

1.2. The Changing Earth

From the perspective of Earth system science, the Earth is seen as a system in which all its constituent materials are subject to constantly changing forces and are, therefore, in constant flux. Thus, the Earth, as “our” life support system, is constantly changing. In parallel, all life is in constant flux in response to these changes: only as individuals (and then only genetically) do we stand still while all around us changes.

Separating the Earth as a support system from human (or indeed all supported) life is naïve. True, life exists in its present form necessarily as a function of the history of conditions present on Earth over geological time. Equally, life is now dependent on present conditions (we breathe air, require food *etc*). However, it is more realistic to view human (all) life as a part of the Earth, that is, as one of its constituents that is subject to environmental forces and is in constant flux. From this perspective, natural change in either part of the system (support system, life) will lead to natural change in the other. Consequently, to expect to be able to hold constant any state in the Earth system, including our own human population, is naïve.

The problem is, of course, that humans are able to manipulate their environment massively in ways (e.g., changes to land cover) that other life cannot. These changes threaten to disturb our life support systems in ways that are both immediate (land cover, pollution) and difficult to predict (e.g., climate change over hundreds of years). The natural survival instinct in humans has led to huge efforts to manage our environment such as to maintain a sustainable life support system for ourselves and our descendants. As a consequence, the Earth system is no longer in climax. Globally, the ability of human *management* to effect change may be small relative to environmental forces. However, locally human management is a very real precursor to survival not only for local human populations, but also for many other forms of life. In short, the human population has become a key player in the Earth system. Its role is to control environmental forces such as to sustain (human) life more effectively. The problem is that in doing so, a (local) unstable plagio-climax is created that requires constant management if it is to be sustained. The pressures from an often increasing population size, and increasing demands of individuals, mean that managing the Earth, as a life support system, is an increasingly complex task. It is in this light that geoinformatics has a key role to play, primarily in providing information to managers and decision-makers. This view of geoinformatics (essentially as a decision-support tool in the context of life support systems) is the view taken throughout this Theme.

1.3. A Note on Science and Technology

In terms of research methodology, one can distinguish between the scientific research methodology and technological research methodology.

In science, the objective is to further understanding (i.e., answer questions of “why”). This is usually achieved via inductive or deductive reasoning. Let us consider the deductive route here. A hypothesis is constructed which, together with a set of initial conditions, must necessarily (deductively) lead to an inescapable conclusion. Thus, given that the initial conditions are valid and error-free the hypothesis can be tested against reality by observation. In practice, the deductive methodology often involves an experiment with some form of control. Any observed differences between the test and the control are necessarily attributable to the difference in the hypotheses (e.g., H_1 v. H_0).

In contrast to science, technological research has as its objective knowledge on “how” to do something (specifically, how to solve a problem). This knowledge is achieved through design and ingenuity, drawing on many different forms of knowledge, including scientific results. Both forms of research are relevant to both life support systems, and to geoinformatics. The general view taken here is that technological research is fundamental to creating the tools and techniques of geoinformatics to solve environmental problems, and science uses these tools to achieve increased understanding of the Earth system.

Applied work (not research) -- for example, that directed at managing the Earth as a system -- employs neither a scientific nor a technological research methodology. However, it is in such work that the fruits of both scientific and technological enquiry are harvested, with greatest direct benefit to humankind. The tools of geoinformatics are increasingly used in sophisticated decision–support systems to manage local environments on the Earth’s surface. Technological research, which creates and improves these tools, is fundamental to their successful execution. Equally, the findings of scientific enquiry underpin the setting of appropriate goals for management. This view of scientific and technological research underpinning management is depicted schematically in Figure1.

Figure 1: Relations between scientific research, technological research and management

The implications for geoinformatics in the context of life support systems are that we need to see geoinformatics as a set of tools: one that is developed by technological research and used in both science related to life support systems and management of those life support systems. Geoinformatics, as a toolbox is, thus, a fundamental life support system in itself. The present local management activities of humans across the globe may not be possible without the support of geoinformatics.

1.4. Scope of this Theme

The scope of this Theme is limited to land surface processes only. The oceans and the atmosphere are excluded.

Central to life support systems is spatio-temporal change and management of that change in a sustainable manner. Spatio-temporal change in Earth surface properties results from natural processes. Certain natural processes are considered as hazards (e.g., diseases, famine, earthquakes, landslides, volcanoes, floods). Such hazards can be modelled, better understood and predicted using the tools of geoinformatics. Spatio-temporal changes in Earth surface properties also result from human influences. Some of these influences have been mentioned above (e.g., land cover change, pollution, biological change and so on). Geoinformatics can also be used to monitor and provide greater understanding of such changes, ultimately to mitigate or reduce their impacts. Such use of geoinformatics as a decision-support tool is central to this Theme.

The most immediate value of geoinformatics to local human populations is in managing the local environment to produce sustainable life support systems. How does one ensure adequate uncontaminated water supply to a local population? How can soil erosion be minimized in an area where agriculture is necessary to sustain life? These are the kinds of questions that geoinformatics is able to or has the potential to answer.

While local management plays a crucial rôle in life support, the focus of this Theme is on global issues at the expense of local issues. This decision is motivated by the fact that ultimately the global environment is the most fundamental life support system, with vast implications across the largest area (globe) and the largest time-scales. All other life-support mechanisms depend on the global environment. This also explains the decision to concentrate on remote sensing as the primary source of data with which to tackle global issues.

This Theme is split into four main Topics. In *Sample Data and Survey*, the focus in the Topic-level writing is on sampling design. The reason for this choice was to highlight this important area of concern prior to introducing (via the individual Articles that comprise the Topic) measurement and analysis in a selection of traditional disciplines.

In *Remote Sensing*, the subject of remote sensing is introduced starting with the basic physical principles (see *Physical Basis of Remote Sensing*), and including articles on *Field Spectrometry* and *Satellite Remote Sensing*. An additional article is included on *Imaging Spectrometry* and the topic is extended to microwave remote sensing in *Radar Systems and Sensing*. Finally, in *NASA Earth Science Enterprise: a New Window on Our World* NASA's Earth System Science programme is described.

In *Statistical Analysis in the Geosciences* four articles are included covering the subjects of *Data Organisation in a GIS*, *Classification and Fuzzy Sets*, *Geostatistical Analysis of Spatial Data* and *Stochastic Modelling of Spatio-Temporal Phenomena in Earth Sciences*. The Topic-level writing includes a broad range of basic statistical tools, including multivariate statistics.

The fourth Topic is *International Cooperation for Data Acquisition and Use*. In the Topic-level writing, Clark introduces some of the basic problems relating to successful data sharing. In *Global Data Networks in the Environmental and Life Sciences* global data networks are described with particular reference to use of the internet, while in the final article of the Theme (*see Developments in Global Land Cover Mapping*), Belward describes international cooperation to produce global land cover maps from remotely sensed imagery.

2. Fundamentals

Any decision support system, such as a geographical information system (GIS), designed to meet a specified objective, is dependent initially on data. Such data are, at least in the first instance, provided by observation or measurement. The way in which measurements are made can have a large effect on the resulting data and their analysis. Therefore, measurement processes should be given careful consideration. Before considering the measurement process in detail, the section below looks at what it is that is measured.

2.1. The Human Environment as a Surface

In section 1, it was established that the Earth system is of interest, in all its complexity. It should be clear that both space and time are of interest. In Newtonian mechanics, three spatial dimensions and one temporal dimension are defined. The three spatial dimensions are treated differently to the temporal dimension because no direction is associated with them. The three spatial dimensions are usually treated differently also because we think of the Earth as a surface. While not strictly (in the mathematical sense) a surface, we can conceptualize a generalized land surface on which we live. Added to this surface are above-surface features such as vegetation (e.g., trees) and infrastructure (e.g., buildings). The land surface is modelled in three spatial dimensions (x, y, h) such that the first two spatial dimensions (x, y) represent location, and the third spatial dimension (h) represents height. In the simplest case, only one height (value of *h*) is possible for any location (x, y) pair, and this value $h(x_0, y_0)$ is connected to $h(x_j, y_j)$ at neighbouring locations (x_j, y_j), $j = 1, 2, \ldots n$. The dimensionality of such a surface, is somewhere between 2 and 3, and it is this reduced space that is of interest when considering the Earth surface. Commonly, elevation *h* is treated as an attribute or variable, alongside other variables, and the dimension of interest is (x, y) (i.e., a 2-D space). Where time is included in the analysis then the space is 3-D (x, y, t), where *t* is the temporal dimension.

2.2. Form and Process

Life and its support systems interact on the land surface (see introduction). This interaction involves change, and such change implies process. It is useful to distinguish between form and process here. Form is the state of any part of the system at a fixed point in time. Forms can be measured, providing a value for a single point (x_0, y_0, t_0) in space and time. More generally, a set of measurements $z(x_i, y_i, t_0)$ at locations (x_i, y_i) for $i = 1, 2, \ldots n$, at a fixed time t_0, relate information on form. By contrast, a process is a law or set of laws that governs change in form. Process is often modelled by a set of rules (e.g., in computer code). However, it is not possible to *measure* process. Rather, it is possible to measure change in form, and from that observed change, imply process. For example, it may be possible to measure $z\left(x_i, y_i, t_j\right)$ at a series of time-slices t_j for $j = 1, 2, \ldots m$.

Decision-support must begin with measurement. Indeed, a large part of the field of geoinformatics may be thought of as instrumentation (and the associated technical expertise) for the measurement of environmental properties. However, to admit this, one must also admit that any analysis starts with form and not process. A very large part of the field of geoinformatics is concerned with characterising and manipulating spatial form. However, given the setting provided by Earth system science above, it should be clear why form alone is rarely the sole interest. We shall return to this point later.

2.3. Measurement of Earth Surface Properties

2.3.1. Phenomena, Properties and Variables

To measure some phenomenon of interest, it is necessary first to define some measurable property. For example, one cannot measure a woodland, but one can measure its biomass. For the variable biomass to be meaningful (see the discussion of the support below) it is also helpful to define it as a density, in the present example as biomass per unit area. When biomass per unit area is measured, a value is produced (e.g., 507 kg ha^{-1}). That value represents the property (or attribute) $z\left(x_0, y_0\right)$ at a given location. For geoinformatics it is important that the location $\left(x_0, y_0\right)$ is also recorded, thus, producing a set of values $\left(z_0, x_0, y_0\right)$ or where time is also recorded $\left(z_0, x_0, y_0, t_0\right)$. Where multiple measurements have been made spatially, a spatial data set is produced $\left(z_i, x_i, y_i\right)$ for $i = 1, 2, \ldots n$, or alternatively $\left(\mathbf{z}, \mathbf{x}, \mathbf{y}\right)$. This measured property is referred to as a variable. Where the variable can be modelled stochastically (using the theory of random variables) it can be referred to as a variate.

Several different types of variable are possible. The most basic distinction arises between continuous and categorical variables. A continuous variable can take any value between given limits. Soil pH is an example. Categorical variables can take one of a set of labels. A land cover classification is an example (e.g., woodland, grassland and built-land are possible labels). Further division is possible. In particular, continuous variables can be ratio (e.g., biomass per unit area) or interval (e.g., temperature) and categorical data can be ordinal (e.g., large, medium, small) or nominal (e.g., land cover).

2.3.2. Measurement Error

All measurements have associated with them some uncertainty. That is, each observation can be modelled as the sum of the unknown "true" value $z\left(\mathbf{x}_0\right)$ (where the vector $\mathbf{x}_0$ is used here in place of $\left(x_0, y_0\right)$) and the unknown error $e\left(\mathbf{x}_0\right)$, thus:

$$\hat{z}(\mathbf{x}_0) = z(\mathbf{x}_0) + e(\mathbf{x}_0) \quad (1)$$

It is important to distinguish between error and uncertainty. Uncertainty arises because the error (and, therefore, the true value) is unknown. If the error were known, there would be an error, but no uncertainty. Many geoinformatics techniques (e.g., photogrammetry, geophysics etc.) have been developed to reduce the uncertainty in measurement. However, some uncertainty must remain, especially in measurements that are difficult to make such as those made in remote locations. (Often it is these measurements that are most valuable). Then, it is the *handling* of uncertainty (rather than its reduction) that becomes important. This point is revisited in the Topics and Articles of this Theme.

2.4. Data v. Model

One of the most important distinctions to make in geoinformatics is that between data and model. As we have seen, data are produced by measurement, and in geoinformatics, spatial data (z, x, y) are of prime interest. If full use is to be made of such data then some form of model is necessary. Here, two broad categories of model are distinguished: analytical and statistical models.

2.4.1. Analytical Models

Analytical models are deterministic and have no stochastic component. They can be applied to model form or process, but here the focus is on their utility in process modelling. Analytical models can be used to model process either indirectly (e.g., as a *transform function* that converts a set of inputs into a set of outputs) or directly (e.g., a *set of rules* that can be applied to an input form to produce an output form). In the context of geoinformatics, spatially distributed process models are of most interest. Such models include the cellular automata applied widely in landscape ecology (see *Biogeography*) and the spatially distributed dynamic models applied in hydrology (see *Land Hydrology*) and geomorphology. In remote sensing, the interaction of radiation with the Earth's surface is modelled as instantaneous, thus requiring an indirect model (typically an analytical transform).

2.4.2. Statistical Models

Statistical models are usually applied to spatial form (c.f. process), although exceptions are actually common and increasing in number. In all cases, statistical models are applied to allow inference (e.g., of some unknown parameters to be estimated or variable to be predicted) given the available data. The statistical models constructed are not expected to replicate reality in any sense. Rather, they are mathematical constructs that allow inference. In a geoinformatics framework, statistical (and, in particular, spatial statistical) models are used for a variety of purposes. These can be classified as (i) characterization, (ii) prediction (e.g., of unknown values, both in space and time), (iii) simulation (i.e., the drawing of *possible* values) and (iv) optimization (e.g., for sampling design).

Whether analytical or statistical, models lie in the realm of mathematics. Thus, models take the form of equations which comprise both variables (which we encountered above) and parameters. A parameter is a constant that defines a model. As a simple example, consider the following equation:

$$y = \alpha + \beta x + \varepsilon \qquad (2)$$

In the above equation, y and x are variables: y is the response and x is explanatory. α and β are parameters. The choices of values for these parameters define the relation between y and x.

2.4.3. Fitting Models

There are two further comments that must be made in relation to data and models. First, a fundamental part of both scientific and technological investigation is the pursuit of fitting models to data. In analytical modelling, models are constructed (via trial and error) that replicate form or process (or at least its consequence, i.e., data) as closely as possible. In statistical modelling, models are fitted to data directly, and the power of subsequent inference depends both on the goodness-of-fit and the quality of the model itself. In both cases, it is important to see data and model as separate. In the next section, measurement and spatial sampling processes are considered in detail.

3. Measurement and Spatial Sampling

We have already established that the phenomena of interest within the Earth system both are constantly in flux and exist in great complexity at a vast range of scales. The question, then, is how should one measure the environment? While this question is far-reaching and raises serious problems and issues, two things are certain. First, it is not possible to measure everything: we must sample. Second, the nature of that sample should be determined in large part by the spatial (or spatio-temporal) nature of the property being investigated. In this section we consider, in some depth, issues of sampling.

3.1. Environmental Measurement

It is possible within the limited 2-to-3-D space in which the surface of the Earth exists to define a multitude of different, spatially varying properties that might be measured. At the most general level, such properties relate to life forms (see *Biogeography*) and their ecology, to the land form itself (see *Landform and Earth Surface*) and its geomorphology, to water (see *Land Hydrology*), and to the underlying rocks and their geology (see *Field Geology*). Beyond the land surface, and beyond the scope of this Theme, further sets of properties relate to the atmosphere and climate, and to the oceans and their circulation. Within each broad subject lies a vast array of sub-disciplines, within each of which lies an even greater array of properties that could potentially be measured. The complexity of the environment is daunting.

Suppose that for a given investigation the objectives are clear and allow definition of a single property of interest, say, biomass per unit area. While "the environment" has been reduced to a single property, thereby, eliminating the complexity described above, spatial variation in that property is still complex. Most importantly, spatial variation in biomass per unit area exists over the entire Earth surface (a geoid, with a diameter of around 8000 km). This complexity in spatial variation is very easy to overlook. Professor Michael Goodchild of the University of California, Santa Barbara has used the following interesting example to emphasize the vastness of the Earth's surface. There are roughly 500,000,000 Km^2 of Earth surface. Suppose a 1 megapel screen is filled, covering roughly 1 km^2, and refreshed every second. It would take 500,000,000 seconds to scan the Earth, or 139,000 hours, or 16 years; in other words a human working lifetime.

Consider the complexity of spatial variation in biomass that can arise in a single 1 km by 1 km area. Such variation might include differences between general vegetation types (e.g., trees, shrubs, grasses) and between individual species (e.g., *Quercus*, *Betula*, *Aldus* etc.), variation in structure (e.g., forest gaps) and health as well as variation within individuals (e.g., spatial distribution of leaves). It is then possible to grasp the enormity of the challenge for humankind. That challenge is, of course, scale. As (very) small individuals on a (very) large Earth, the challenge is to find ways of measuring the important properties at an appropriate scale such as to provide the information of interest. Ideally, such information should be provided efficiently (i.e., with the minimum data). The remainder of this section considers sampling issues, with particular emphasis on issues of scale.

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Bibliography

Atkinson, P.M. (1996). Optimal sampling strategies for raster-based geographical information systems. *Global Ecology and Biogeography Letters* **5**, 271-280. [An article on sampling design for data entry into GIS].

Atkinson, P.M. (1999). Geographical information science: geostatistics and uncertainty. *Progress in Physical Geography* **23**, 134-142. [The article reviews geostatistics and GIS with reference to non-stationary (local parameter) modelling].

Atkinson, P.M. and N.J. Tate. (2000). Spatial scale problems and geostatistical solutions: a review -- *Professional Geographer* **52**, 607-623. [Introduces basic sampling issues in a geographical context].

Burrough, P.A. (1998). Dynamic modelling and geocomputation. In Longley, P.A., Brooks, S.M., McDonnell, R. and MacMillan, W., editors, *Geocomputation: a Primer*, 165-191pp. Chichester: Wiley. [A very useful introduction to spatially distributed dynamic modelling within the context of GIS].

Burrough, P.A. and McDonnell, R.A., (1998). *Principles of Geographical Information Systems. Spatial Information Systems and Geostatistics.* New York: Oxford University Press. [An excellent introduction to GIS from a physical geography viewpoint].

Chalmers, A.F. (1999). *What is This Thing Called Science?* -- Open University Press: Buckingham. [A standard reference on the scientific research methodology].

Chiles, J.P. and Delfiner, P. (1999). *Geostatistics. Modelling Spatial Uncertainty*. Chichester: Wiley. [An excellent comprehensive reference on geostatistics].

Csillag, F., Kertész, M. and Kummert, Á. (1996). Sampling and mapping of heterogeneous surfaces: multi-resolution tiling adjusted to spatial variability. *International Journal of Geographical Information Systems* **10**, 851-875. [A landmark paper on multi-resolution tiling and quadtrees. That is, matching sampling resolution to frequency of spatial variation].

Curran, P.J. (1985). *Principles of Remote Sensing*. Longman: Harlow. [Easy to read introduction to remote sensing].

Fotheringham, S., Brunsdon, C. and Charlton, M. (2000). *Quantitative Geography. Perspectives on Spatial Analysis*. London: Sage. [A wonderfully easy-to-read book on quantitative geography in general].

Goodchild, M., Steyaert, L., Parks, B.O., Johnston, C.O., Maidment, D.R., Crane, M.P. and Glendinning, S., editors, (1996). *GIS and Environmental Modelling: Progress and Research Issues*. Fort Collins, CO: GIS-World Books. [Examines the links between GIS and environmental (e.g., dynamic) modelling].

Goodchild, M.F. and Gopal, S. (1989). *Accuracy of Spatial Databases*. London: Taylor and Francis. [One of the first books to consider errors in GIS in an explicit way].

Goovaerts, P. (1997). *Geostatistics for Natural Resources Evaluation*. New York: Oxford University Press. [An easy-to-read and excellent introduction to geostatistics which is sympathetic to the GIS reader].

Heuvelink, G.B.M. (1998). *Error Propagation in Environmental Modelling with GIS*. London: Taylor and Francis. [An excellent monograph on models for how errors propagate through the GIS cycle].

Journel, A.G. (1996). Modelling uncertainty and spatial dependence: stochastic imaging. *International Journal of Geographical Information Systems* **10**, 517-22. [Provides a useful introduction to conditional simulation].

Lane, S.N., Bradbrook, K.F., Richards, K.S., Biron, P.A. and Roy, A.G. (1999). The application of computational fluid dynamics to natural river channels: three-dimensional versus two-dimensional approaches. *Geomorphology* **29**, 1-20. [Considers the merits of 2-D v. 3-D CFD models for river channels].

Longley, P.A., Brooks, S.M., McDonnell, R. and MacMillan, W. (editors) (1998). *Geocomputation: a Primer*. Chichester: Wiley. [One of the first volumes on GeoComputation, which is similar to GIS but emphasises computational analysis].

McBratney, A.B., and Webster, R. (1986). Choosing functions for semi-variograms of soil properties and fitting them to sampling estimates. *Journal of Soil Science* **37**, 617-639. [An outstanding reference on fitting models to variograms].

Tso, B. and Mather, P.M. (2001). *Classification Methods for Remotely Sensed Data*. Taylor and Francis: London. [An excellent textbook introduction to classification techniques in remote sensing].

Van Gardingen, P.R., Foody, G.M. and Curran, P.J. (1997). *Scaling Up. From Cell to Landscape*. Cambridge University Press: Cambridge. [Issues of scale in a remote sensing context].

Van Groenigen, J.W. and Stein, A. (1998). Constrained optimization of spatial sampling using continuous simulated annealing. *Journal of Environmental Quality* **27**, 1078-1086. [An excellent reference on the Geostatistical design of optimal sampling strategies].

Biographical Sketch

Peter Atkinson is full Professor of Geography at the University of Southampton. Prior to joining the University of Southampton, he spent three years as a post-doctoral researcher at the Department of Geography, University of Bristol. He obtained his B.Sc. degree from the Department of Geography, University of Nottingham in 1986, and his Ph.D. degree from the Department of Geography, University of Sheffield (NERC CASE award with Rothamsted Experimental Station) in 1990. His main research interests are in spatial statistics and spatial modelling, with particular emphasis on geostatistics, GIS, remote sensing and spatially distributed dynamic modelling. His substantive interests are varied and include biogeography, ecology, epidemiology, soil survey, geomorphology, land surface hydrology, and a range of natural hazards within these (e.g., disease, landsliding, flooding). Peter Atkinson has published numerous refereed journal articles. In addition, he has edited five books on remote sensing or GIS and seven journal special issues. He is joint Editor of *International Journal of Remote Sensing Letters*, and is an Editorial Board member for several journals. He has been PI on several grants and contracts and currently sits on numerous international scientific committees.