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Review Article

Geographic Information System: A Potential Tool for Resource Management in Changing Environment

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A B S T R A C T

The geographic context is essential both for environmental research and for policy-oriented resource management. Geographic information systems are as a result increasingly important computing applications in this domain, and an understanding of the underlying principles of geographic information science is increasingly essential to sound scientific practice and discuss advances in GIS analysis and modeling, in the supply of geographic data for GIS, in software design, and in GIS representation. GIS based modeling continues to support modeling through the coupling of software. GIS software design is being revolutionized by two developments in the information technology mainstream: the trend to component-based software and object-oriented data modeling. Advances in GIS representation focus largely on time, the third spatial dimension, and uncertainty. The concluding section identifies three significant and current trends: toward increasing interoperability of data and services, increasing mobility of information technology, and increasing capabilities for dynamic simulation.

Introduction

Geographic facts are in themselves not as valuable and significant as general facts, but they are essential if general facts are to be extracted through the study of specific areas or applied in specific areas to provide the boundary conditions and parameters that are needed in order to forecast, to evaluate planning options, or to design new structures. The terms *geographic* and *geospatial* to describe collections of facts about specific places in the environment, and *spatiotemporal* to describe collections of facts about specific places at specific times. Clearly a high proportion of the data needed for environmental management are geographic and, increasing quantities of geographic data take the form of electronic transactions, vast amounts of geographic data are now collected daily by imaging satellites and distributed via the Internet, and increasing amounts are collected by networks of ground-based sensors and through field observation.

Environmental management has been a prime motivator of developments in GIS, and a major area of application, Environmental management continues to motivate developments in GIScience and their implementation in GIS. Geographic data and GIS are of such importance to the environmental disciplines that today we tend to think of them as indispensable parts of the research, teaching, and policy arenas. Abundant examples of GIS use in this context are available in textbooks, journals, conference proceedings, and on the World Wide Web (WWW). The argument for geographic data and GIS, and more generally for taking a geographic or spatial perspective on the environment, is essentially twofold Goodchild MF, Anselin L, Appelbaum RP, Harthorn BH. 2000.

In recent years much interest has developed in the social context of GIS use. In the early years, when the cost of entry into GIS was much higher, access to it was largely restricted to large corporations and government agencies. But the steady fall in hardware and software costs over the past three decades has led to almost universal access, and community groups are now frequent users of GIS and rely on its capabilities to build arguments for and against local developments. The role of GIS in the decision making process is the focus of the growing research field of Public Participation GIS Craig WJ, Harris TM, Weiner D, eds. 2002.

GIS analysis and modeling

Types of Geographic Data

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

However, this simple model fails in one crucial respect: There are many distinct types of geographic data. GIScientists distinguish between two fundamentally different conceptualizations of the geographic world Couclelis H. 1992, Goodchild MF. 1992, Worboys MF. 1995. In the *continuous field* view, the surface of the Earth can be described by mapping a set of variables, each of which is a single-valued function of location, and perhaps time. In the second, or *discrete object* conceptualization, the Earth's surface is a space littered with objects.

The objects may overlap, and there may be empty space between them. The shapes of lines are commonly represented as sequences of points connected by straight lines, and areas as closed sequences (the terms *polyline* and *polygon* are used respectively). Continuous fields present a more difficult representation problem, In practice, any field representation must be an approximation for this reason, and six methods of approximation are commonly used in GIS (discussed here in the two-dimensional case):

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

Irregularly spaced sample points The continuous fields of meteorology, e.g., atmospheric temperature, pressure, and precipitation, are sampled at irregularly spaced measuring stations.

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

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

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

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

Of these six, the first two and the last are inherently different from the third, fourth, and fifth. While the latter three can be queried to obtain the value of the field at any location, the former three record values only at certain locations: points in the case of the first two and lines in the case of the last. One might term the latter set complete representations, and the former set incomplete representations, for this reason, though note that completeness does not imply perfect accuracy. In order to support queries about the values of the field, or to support resampling, or various forms of visualization, an incomplete representation must be coupled with a method of *spatial interpolation*, defined as the means to estimate the field's value at locations where value is not recorded. A substantial number of methods of spatial interpolation are available Goovaerts P. 1997, Lam NS-N. 1983, Isaaks EH, Srivastava RM. 1989, many of them implemented in GIS. The representations of both discrete objects and continuous fields fall into two categories and are often described in these terms. Methods that record coordinates are termed *vector*, and they include all of the discrete object representations, plus the irregularly spaced sample points, irregular polygons, triangular mesh, and digitized isoline representations of fields. *Raster* methods, on the other hand, establish position implicitly through the ordering of the array and include the regularly spaced sample point and rectangular cell representations of continuous fields. For this reason, rasters are often loosely associated with continuous fields, and vectors with discrete objects, but the association is more likely to confuse than to illuminate.

Developments in GIS Analysis

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

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

Simple queries, which return results already existing in the database;

Measurements, which return measures of such properties as distance, length, area, or shape;

Transformations, which create new features from existing features;

Descriptive summaries, which compute summary statistics for entire collections of features;

Optimization, which results in designs that achieve user-defined objectives, such as the search for an optimum location; and

Hypothesis testing in which statistical methods are used to reason from a sample to a larger population.

Each of these categories might apply to any type of data, and to both discrete object and continuous field conceptualizations. Today, GIS is used in a vast array of application domains, many of them strongly associated with the environment and with resources. Papers describing research that has made use of GIS to study problems in the environment and in resources appear in specialized journals, and several collections of papers have been published recently as books. GIS applications to environmental health have been described by Gatrell & Loytonen 1998, Cromley & McLafferty 2002, Briggs 2002, and Lang 2000. Haines-Young *et al.,* 1993 and Johnston 1998 describe applications in landscape ecology. A forthcoming book by Bishop 2003 contains solicited chapters describing the use of GIS in mountain geomorphology.

Advances in GIS Representation

A GIS representation is a set of rules for converting aspects of the real world into the language of computers, which is limited to a two-character alphabet. Standards such as MP3 provide these rules for other domains such as music; in GIS, raster and vector approaches provide two general classes of coding schemes, the specific details determined largely by the GIS developer. GIS inherits many of its core concepts from paper maps, and it is still common for GIS to be explained as a technology for capturing and processing the contents of maps. But maps impose many restrictions on geographic data that are not necessary in a digital environment Goodchild MF. 2000. First and perhaps most important, maps must of necessity be static because once printed it is difficult to modify them, and it follows that maps tend therefore to capture only what is relatively static about the Earth's surface. The potential to incorporate time, to move from a spatial to a spatiotemporal basis for GIS, has stimulated much research over the years.

Langran 1992 reviewed early work on the topic, and Peuquet 2002 provides a recent overview of the methodological basis of space and time. Today, GIS is increasingly used to store and analyze data on space-time tracks, on events occurring at specific points in space and time, and on changes through time detected by remote sensing.

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

GIS is now an indispensible tool which is widely accepted as resource management in changing environmental situations. Although it is not the only computer application relevant to the field, or even the only one relevant to geographic data, it is without doubt the dominant application in the development of environmental policy and in environmental decision making. Many different GIS products exist from commercial vendors, and several have been developed by academics, some under the open-source paradigm that permits free use. The continuing progress on interoperability and associated technologies, which will increasingly allow researchers and managers to access and use distributed data and services in what will eventually become a largely seamless and global computing environment.

Another is mobility and the increasing ability to process and analyze information in the field, as it is collected. Field information technologies and field sensors have the potential to revolutionize the practice of environmental science and management and to make it possible to perform virtually all tasks in the field, with sophistication and accuracy of environmental models and the increasing ability to use them and integrate them into different research and policy environments will mean that GIS use becomes more and more forward-looking and relevant to the broader objectives of policy, rather than the narrower objectives of inventory and description.

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