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Yuji Murayama *Editor*

Progress in Geospatial Analysis

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Yuji Murayama
Division of Spatial Information Science
Graduate School of Life and Environmental Sciences
University of Tsukuba, Tsukuba, Ibaraki, Japan

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Preface

This book discusses the current trends in methods and applications of geospatial analysis and highlights future development prospects. It aims to provide a comprehensive discussion on data processing techniques, current practices with theories and models of remote sensing (RS) and geographical information systems (GIS), and empirical studies of geospatial analysis.

Data acquisition and processing techniques such as remote sensing image selections, classifications, accuracy assessments, models of GIS data, and the spatial modeling process are focused on in the first part of the book. In the second part, theories and methods, including fuzzy sets, spatial weights and prominence, geographically weighted regression, weight of evidence, Markov–cellular automata, artificial neural networks, agent-based simulation, multi-criteria evaluation, analytic hierarchy process, and a GIS network model are included. Part III presents selected best practices on geospatial analysis, focusing on geographical phenomena. Most of the chapters are original and a few, especially for applications, are reprints from international journals and proceedings.

This book is written for academicians, researchers, practitioners, and advanced graduate students. It is designed to be read by those new or starting out in the field of geospatial analysis, as well as by those who are already familiar with the field. The chapters are selected from experienced authors in such a way that readers who are new to the field will gain an important overview and insight. At the same time, those readers who are already practitioners in the field will gain from the advanced and updated materials and state-of-the-art developments in geospatial analysis.

Most of the contributors to this book are current faculty members, staff members, graduates, and PhD candidates of the Division of Spatial Information Science, University of Tsukuba, Japan. The Division, which was established in 2000 for including Geographical Information Science within the Doctoral Program in Geoenvironmental Sciences, provides an enabling research environment where faculty members, staff, and students work together to advance knowledge in GIS and remote sensing techniques in different areas of interest.

My sincere thanks go to the staff members of the Division of Spatial Information Science, University of Tsukuba, especially to Mr. Konstantin Greger, whose sharp eyes and skills with computers helped make the manuscript become a better book.

Tsukuba, Ibaraki, Japan Yuji Murayama

About the Editor

Yuji Murayama, Professor, Division of Spatial Information Science, Graduate School of Life and Environmental Sciences, University of Tsukuba, Japan. Email: mura@geoenv.tsukuba.ac.jp, Web: http://giswin.geo.tsukuba.ac.jp/sis/en/faculty.html. Books published: Murayama, Y. and Thapa, R. B. eds. (2011). *Spatial Analysis and Modeling in Geographical Transformation Process: GIS-based Application*. Dordrecht: Springer, 300p. Kamusoko, C., Mundia, C. N. and Murayama, Y. eds. (2011). *Recent Advances in Remote Sensing and GIS in Sub-Saharan Africa*. New York: Nova Publishers, 211p. Murayama, Y. and Du, G. eds. (2005). *Cities in Global Perspective: Diversity and Transition*. Tokyo: College of Tourism, Rikkyo University with IGU Commission, 626p. Murayama, Y. (2000). *Japanese Urban System*. Dordrecht: Kluwer Publishers, 271p. Murayama, Y. (1991). *Spatial Structure of Traffic Flows*. Tokyo: Kokon-Shoin, 311p.

Contributors

Bingliang Cui School of Geography, South China Normal University, Guangzhou, People's Republic of China

Ronald C. Estoque Division of Spatial Information Science, Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan

Don Mariano Marcos Memorial State University, Bacnotan, La Union, Philippines

Courage Kamusoko Overseas Operations Division, Asia Air Survey Co. Ltd., Tokyo, Japan

Formerly in Integrative Environmental Sciences Program, University of Tsukuba, Tsukuba, Japan

Duong Dang Khoi Faculty of Land Administration, Hanoi University of Natural Resources and Environment, Vietnam

Formerly in Division of Spatial Information Science, Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan

Ko Ko Lwin Division of Spatial Information Science, Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan

Kondwani Godwin Munthali Division of Spatial Information Science, Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan

Yuji Murayama Division of Spatial Information Science, Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan

Rajesh Bahadur Thapa Earth Observation Research Center, Space Applications Mission Directorate, Japan Aerospace Exploration Agency (JAXA), Tsukuba, Japan

Formerly in Division of Spatial Information Science, Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan

Changping Zhang Faculty of Regional Development Studies, Toyo University, Tokyo, Japan

Formerly in Graduate School of Geoscience, University of Tsukuba, Tsukuba, Ibaraki, Japan

Yaolong Zhao School of Geography, South China Normal University, Guangzhou, People's Republic of China

Formerly in Division of Spatial Information Science, University of Tsukuba, Tsukuba, Ibaraki, Japan

Contents

Chapter 1
Introduction: Geospatial Analysis

Yuji Murayama

1.1 What Is Geospatial Analysis?

Although the term "geospatial analysis" is widely used in the academic world, its definition is not clear even in the field of geographical information science (GIS). In this book, we define geospatial analysis as a GIS-based approach to analyze geographically referenced information using methods such as statistics, information theories, computational geometry, and geovisualization techniques. Its goal is to find the driving forces of changes on the earth's surface, and analyze the geographical phenomena in order to understand their processes and mechanisms. Finally, it allows to suggest appropriate policy planning and decision making for sustainable development of a region to be suggested.

"Geospatial" information is considered a part of "spatial" information, which receives wide recognition in GIS communities. Here, geospatial data are limited to those on the earth's surface which are geographically referenced by address, place name, latitude/longitude, and so on. Geological phenomena inside the earth, the free atmosphere far above the earth's surface, and the topography on the Moon and Mars, for example, are not encompassed by the category of geospatial data in this book. Furthermore, architectural concepts like building structure and room arrangement in houses are also outside our research territory, although they are embraced in spatial data. In this regard, field-based empirical studies using geospatial techniques are conducted mainly within the geography-related disciplines.

Y. Murayama (✉)
Division of Spatial Information Science, Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan
e-mail: mura@geoenv.tsukuba.ac.jp

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1.2 Quantitative Revolution

The origin of geospatial analysis can be traced back to the 1950s, when in North America the contribution of academics to society in general was required by the penetration of practicalism (Murayama 2004a). Geography was criticized because its methodological framework was old-fashioned and insufficient to satisfy social needs. Against this backdrop, quantitative methods and theoretical models oriented to law-making were pursued, and these were applied in problem-solving studies (Murayama 2004b). This academic movement was called the *Quantitative Revolution* in geography (Burton 1963). New methodologies, including network approaches using graph theory, central place formulation, point pattern analysis, regionalization and classification techniques employing multivariate analysis, and location-allocation problems were developed (Berry and Marble 1968).

In the 1970s, geospatial analysis with a time dimension, that is, spatiotemporal analysis, emerged and quickly became popular. It embraces time geography, behavioral geography, studies of changes in land use/cover, spatial diffusion and interaction modeling, and so on. A strong emphasis was placed on the conceptual switch from static to dynamic thinking, in other words, from the spatial structure to spatial process studies. In the late 1970s, computer mapping was developed as a type of analytical cartography, paving the way for geovisualization studies linked with GIS (Tobler 1976).

1.3 GIS Revolution

In the 1980s and 1990s, new techniques in geospatial analysis were exploited and implemented in GIS software (Murayama 2001). Advanced geospatial analysis became available without programming via open-source freeware such as GRASS, SPATSTAT, and R Package. Methodologically, great interest was focused on spatial homogeneity and heterogeneity (Anselin 1988). This concept was developed by further studies on local spatial autocorrelation, geographically weighted regression (GWR), spatial weight metrics and prominence, Kernel density, modifiable area unit problems, trend surface, and so on.

Geospatial analysis is interdisciplinary in nature. To enhance its operability, strong cooperation among adjacent disciplines is indispensable. In the 1990s, sophisticated GIS software was invented through teamwork which brought together regional science, information science, computation geometry, and statistics. The analytical functions became powerful due to the integration of raster-based GIS and vector-based GIS. Furthermore, the combination of GIS with remote sensing (RS) enhanced the usability of geospatial analysis, where useful techniques in RS such as spatial metrics, land use/cover classification, fuzzy sets, and so on, were effectively introduced within the GIS framework (Murayama and Thapa 2011a).

Today, tremendous amounts of geospatial data are ceaselessly produced and have become immediately available in the GIS environment. This data-rich condition, along with increasing computing power, is enabling the development of advanced geospatial data mining. In the 1990s, geocomputation was developed with the use of fine image data from RS, and socioeconomic micro-data such as individual information from censuses and volunteered information (Openshaw and Abrahart 2000; Murayama and Thapa 2011a). The availability of high-resolution images from Quick Bird, IKONOS, and ALOS, for instance, is accelerating the micro-approach within cities, which is called urban remote sensing (Yang 2011). Today, geocomputational techniques are rapidly becoming strong tools for process-based studies where the future is predicted based upon the process from the past to the present. These techniques include neural networks, cellular automata, agent-based modeling, genetic algorithms, self-organizing mapping, and so forth. Since 1996, a geocomputation conference is held every 2 years, where geographers, information scientists, computer programmers, and other experts gather from all over the world to reflect on work within the field of geocomputation from an interdisciplinary perspective (http://www.geocomputation.org/).

The *GIS revolution* has brought methodological and conceptual shifts: from model-driven to data-driven, from deductive to inductive, from top down to bottom up, from aggregate to disaggregate, from discrete to continuous, from lagged time to real time, from static to dynamic, from quantitative to qualitative, and from linear to non-linear (Murayama and Thapa 2011b). From this revolution, it could be argued that geospatial analysis with GIS is more a useful tool in formulating hypotheses than it is in verifying them.

The book consists of 17 chapters. Chapter 1, the introduction, traces the evolution/origin of geospatial analysis using GIS-based techniques, and discusses the usefulness of theories, techniques, and methods for analyzing geographical processes occurring on the earth's surface. Then an overview of each chapter is given.

1.4 Geospatial Data Acquisition and Processing

In Part I, geospatial data acquisition and processing are discussed (Chaps. 2 and 3).

Chapter 2 focuses on the preprocessing of remotely sensed data and classification methods. Information extraction from satellite image data requires appropriate image-processing methods and techniques. The overall aim is to extract the information and explore the spatial patterns of land-surface objects, that is, land cover patterns from the classified satellite imagery known as a thematic map. Furthermore, this chapter presents theoretical procedures and techniques to produce useful information from such thematic maps. Significant technological advancements in data acquisition and analysis in recent years have made it easier to analyze the spatiotemporal dynamics of landscape changes using multispectral classification techniques with various statistical rules. Finally, this chapter discusses the various methods of assessing the classified image ranging from field-based validation to visual interpretation with high-resolution satellite images.

Chapter 3 focuses on geospatial data collection methods, database design and construction, and modeling with GIS. Geospatial data collection, including remote sensing, field surveying, and other in-house GIS data conversion processes (i.e., scanning, georeferencing, digitizing, etc.), is an important task for many geospatial information users. Traditional field data collection (i.e., pen-and-paper-based) is a bulky and time-consuming task. However, recent developments in mobile communication, global navigation systems, the Internet, and portable computational devices such as smartphone, netbooks or ultra-mobile personal computers (UMPCs) allow us to carry out field data collection in a timely manner. Moreover, under the client-server setting for field data collection, a field user may take advantage of digital repositories prepared for data collection (i.e., base maps, satellite images, and other ancillary data) as well as information resources more generally available via the Web. Proper geospatial data collection and conversion are required to support spatial analysis with GIS, which is vital for accurate decision making. Geospatial data processing is at the heart of the task in many GIS analyzes.

1.5 Geospatial Theories and Methods

GIS is designed to store, retrieve, manipulate, analyze, and visualize geospatial data. On the other hand, the uncertainty which affects the accuracy of maps and geospatial analysis results always exists in the data because of the limitations of human cognition of geographical phenomena or the resolving power of surveying instruments. Part II is composed of nine chapters (Chaps. 4 through 12), and aims to review the existing theories and methods in geospatial analysis, particularly in land use/cover modeling and GIS network data models.

Chapter 4 analyzes the fuzziness of geographical phenomena and classifies them into three aspects: the fuzziness of the distribution of the geographical phenomena or concept of a geographical entity, the fuzziness derived from spatial relationships, and the fuzziness derived from geospatial analysis and spatial reasoning operations. Fundamental fuzzy set theory, including the definition of a fuzzy set, fuzzy set operations, and fuzzy relationships and membership functions, is summarized in the representation of such fuzzy phenomena. Applications of fuzzy set theory in GIS are reviewed according to the sequence of fuzzy representations of geographical entities and their distribution, fuzzy spatial relationships, and fuzzy operations in spatial reasoning. Then, an example of a field-based integrated spatial reasoning model in the case of a constraint satisfaction problem (CSP) is given to synthetically illustrate the above-mentioned three fuzzy aspects. Finally, the author considers the future research directions of fuzzy set theory in applications using GIS.

Chapter 5 shows that in geospatial analysis of geographical phenomena, a region or a city under study might be divided into several small areal units such as a regular square tessellation or administrative units emerging in irregular shapes. The spatial interrelation between areal units can be expressed as different definitions of the weight coefficient. For example, the spatial structure of areal units might be defined as the spatial contiguity, which is treated as a spatial weights matrix $\boldsymbol{W}$ with a binary variable. This chapter also explains how to define and create the spatial weight, which is an expression of the spatial dependence between areal units. Four types of weight functions are introduced here. An area which has special geometric attributes and keeps significant spatial correlation close to adjacent areas is called a *prominent area*. As an application of the spatial weights matrix, the prominence of irregular areas can be measured by the *prominence index*, which is a stationary distribution of a Markov chain transition matrix that is identical to a spatial weight matrix. An empirical study in this chapter shows that generalized weight matrices are more appropriate for measuring the prominence rather than the distance decay and k-order.

Chapter 6 explains GWR, which is a technique for spatial statistical modeling used to analyze spatially varying relationships between geographical variables. Unlike the traditional regression framework, GWR allows local rather than global parameters to be estimated. In this chapter, the authors discuss the theoretical basis of the GWR method and modeling. Some of the current best practices for understanding urban and regional problems, for instance, regional analysis of wealth and land use/cover, driving forces behind deforestation and afforestation, and so on, are highlighted. GWR is one of the recent developments of local spatial analytical techniques, and it has been part of the growing trend in GIS toward local analysis.

Chapter 7, which deals with Bayesian theory, focuses on the weight of evidence (WofE) method and its applications in GIS. WofE, which is entirely based on the Bayesian approach of conditional probability, is traditionally used by geologists to point out areas which are favorable for geological phenomena such as seismicity and mineralization. Recently, the WofE method has been used to combine spatial data from a variety of sources to describe and analyze interactions, provide evidence for decision making, and construct predictive models. This chapter discusses the theoretical basis of WofE and presents best modeling practices. Basically, this method concerns the likelihood of detecting a certain event, which could be a given category of land use/cover change such as a change from an agricultural area to a built surface, in relation to potential evidence (proximity to urban centers, roads, water, etc.), often called the driving factors of change.

Spatial simulation models such as the Markov cellular automata (MCA) are critical for land use/cover change modeling because models are needed to gain insights into land use/cover change processes at many spatial and temporal scales. The MCA model combines cellular automata with Markov chains and GIS-based techniques such as multicriteria evaluation (MCE) and WofE in order to simulate land use/cover changes. The Markov chain process controls temporal dynamics among the land use/cover classes, while spatial dynamics are controlled by local rules determined either by the cellular automata mechanism or by its association with transition potential maps computed by WofE and MCE techniques. Chapter 8 reviews the methodological developments of the MCA model, as well its current status and future prospects based on criteria such as modeling techniques, data requirements, calibration, and validation. Thus, issues raised in this chapter could contribute to the improvement of future MCA land use/cover change models.

Chapter 9 outlines the progress of artificial neural networks, architectures, algorithms, and future developments in geospatial analysis with GIS. Their applications are reviewed with land use/cover change analysis and modeling. Many artificial neural network architectures have been developed over the past years. One of the most popular is the multilayer perceptron (MLP) neural network. From a geospatial analysis point of view, MLPs have been shown to be a universal and highly flexible function approximation tool for any data. This chapter gives a comprehensive review of the history and basic architecture of MLPs. The use of MLPs for land use/cover classification is presented as a representative type of data-pattern recognition. Finally, future trends in the development of MLPs are briefly summarized.

Chapter 10 reviews multiagent simulation models to understand land-use change management and sustainability in the area of forest loss (deforestation). An attempt is made to assess the sustainability of deforestation management from the perspective of individual decisions made at the farm or household level. Agent-based models (ABMs) continue to receive wide attention as a method of modeling complex real-world applications. Founded on the pretext of understanding the non-linearity of natural systems, the multidisciplinary ABM originates primarily from artificial intelligence. This chapter delves into the history of complex systems and connects it to present-day fundamental principles of defining and designing agents. It then highlights the basic tenets of agent modeling implementation, which include a discussion on available ABM development platforms. This chapter also contextualizes the agent, its environment, and its interaction when applications of ABM in land use/cover modeling are presented and addressed. All this adds to the available literature on ABMs in the hope that by presenting both the past and present, modelers will be able to distinguish between and develop new ABM approaches for the future.

Chapter 11 discusses multicriteria decision analysis (MCDA). Since its development in the 1970s, the analytic hierarchy process (AHP) has been an important tool for decision makers and researchers. It presents a flexible, step-by-step, and transparent way of analyzing complex problems in a MCDA environment based on experts' preferences, knowledge, and judgments. There has been a growing interest in using this method in the last two decades or so, and its scope of application has been expanding, especially in the field of geospatial analysis. This chapter also reviews the basic principles of AHP, its historical development, and its applications as a decision support tool for GIS-based MCDA. Major findings show that AHP has been implemented in various fields of geospatial analysis in various countries around the world. This indicates how versatile and useful AHP is as a decision support tool. However, the review also shows that researchers have still not achieved consensus on certain issues concerning the implementation of AHP as a weighting method for GIS-based MCDA. Some of these issues include considerations about the method of capturing expert opinion using the pair-wise comparison method, the method of aggregation of individual expert's ratings (in cases where consensus ratings are not used), and the method of standardizing the individual factors involved in a GIS-based MCDA. These issues are crucial; thus, careful attention is needed when using AHP as a decision support tool for GIS-based MCDA. Nevertheless, because of AHP's effectiveness in evaluating problems involving multiple and diverse criteria and the measurement of trade-offs, its simplicity and robustness, and its precision and ease of use, its applications will undoubtedly continue to expand in fields of both non-spatially and spatially based decision-making environments.

Chapter 12 discusses the GIS network model and its applications. A network is an interconnected set of points and lines that represent possible routes from one location to another. Road network models play a critical role in urban planning, emergency preparedness, retail market and market competition analysis, public facility management, and other planning and decision-making processes. Understanding the road network patterns in urban areas is important for human mobility studies, because people live and move along the road networks. Network data models allow us to solve daily activities such as finding the shortest path between two locations, looking for the closest facilities within a specific distance, and estimating driving time. A network model can include a multilayer model representing, for example, a railway system, a subway system, and a bus system to solve problems using multiple modes of transportation in an urban area. Many commercial GIS data models composed of layers such as points (nodes) and lines (links) comprise separate layers. This is called a layer-based approach. These nodes and links can also be represented as object classes; this type of model is known as an object-oriented network data model, and is still in the design phase. The development of 3D network models and concepts in GIS can solve these complex multilayer network solutions. Moreover, the combination of Internet technology and user-friendly Web-GIS provides an opportunity to perform interactive network analysis to make spatial decisions in a timely manner for local residents and city planners through Web-based GIS systems.

1.6 Applications in Geospatial Analysis

Part III provides five applications (Chaps. 13 through 17) in geospatial analysis employing GIS, remote sensing, and global positioning systems.

The complexity of urban systems requires integrated tools and techniques to understand the spatial process of urban development and project future scenarios. In this connection, Chap. 13 aims to simulate urban growth patterns using a Bayesian probability function in the Kathmandu metropolitan region in Nepal. Like many cities in the developing world, it has been facing rapid population growth and daunting environmental problems. Three time-series land-use maps at a fine scale (30 m resolution) derived from satellite remote sensing covering the last three decades of the twentieth century were used to clarify the spatial process of urbanization. Based on historical experiences of land-use transitions, the authors adopted the WofE method integrated in a cellular automata framework to predict the future spatial patterns of urban growth. The authors extrapolated urban development patterns to 2010 and 2020 under the current scenario across the metropolitan region. Depending on local characteristics and land-use transition rates, this model produced a noticeable