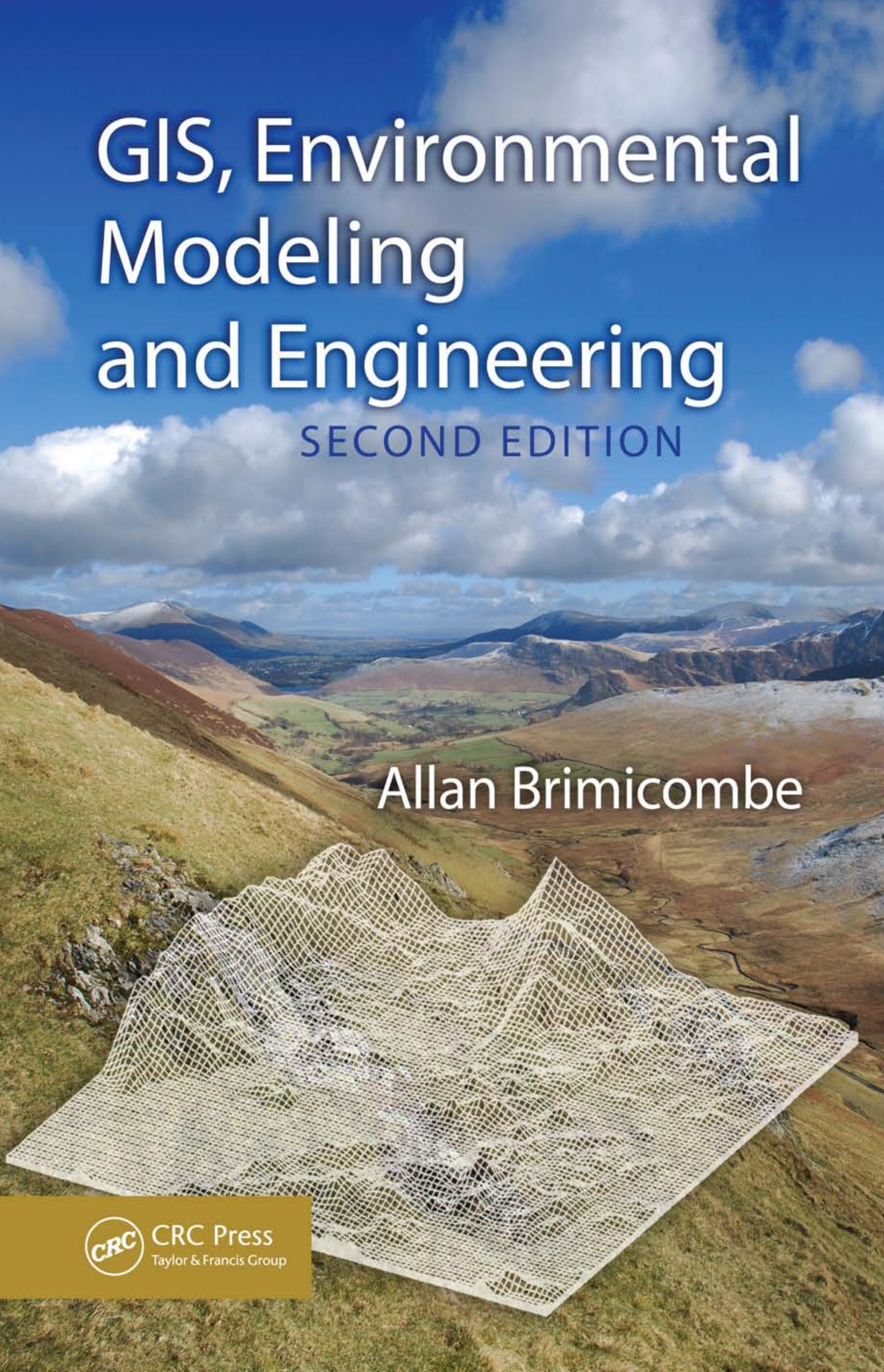
GIS, Environmental Modeling and Engineering

SECOND EDITION

Allan Brimicombe



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First Edition

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Abbreviations

ABM: agent-based modeling
AI: artificial intelligence
ANN: artificial neural networks
API: aerial photographic interpretation
BMP: basin management plans
CA: cellular automata
CBR: case-based reasoning
CN: runoff curve number
DDE: dynamic data exchange
DEM: digital elevation model
DIME: dual independent map encoding
DSS: decision support systems
EIA: environmental impact assessment
EIS: environmental impact statement
fBm: fractional Brownian motion
FDM: finite difference method
FEM: finite element method
FoS: factor of safety
GI: geo-information
GIS: geographical information systems
GLUE: generalized likelihood uncertainty estimator
GPS: global positioning system
GPZ: Geo-ProZone, geographical proximity zones
HKDSD: Drainage Services Department, Hong Kong Government
HTML: hypertext markup language
ICS: index of cluster size
IDW: inverse distance weighted
KBS: knowledge-based systems
LBS: location-based services
LiDAR: light distancing and ranging
MAUP: modifiable areal unit problem
MC: Monte Carlo (analysis)
MCC: map cross-correlation
NEC: no effect concentration
NEPA: National Environmental Policy Act (U.S.)
NIMBY: not in my back yard
NVDI: normalized vegetation difference index
OAT: one-at-a-time
OLE: object linking and embedding
OO: object-oriented

ORDBMS: object-relational database management system
PCC: proportion correctly classified
PEC: predicted environmental concentration
PDF: probability density function
PGIS: participatory GIS
QAE: quality analysis engine
RAISON: regional analysis by intelligent systems on microcomputers
RDBMS: relational database management system
REA: representative elementary area
RS: remote sensing
SA: sensitivity analysis
SCS: Soil Conservation Service (U.S.)
SDSS: spatial decision support systems
TIN: triangular irregular networks
UA: uncertainty analysis
WWW: world wide web

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1

Introduction

I wish to begin by explaining why this book has been written. Peter Fleming, in writing about his travels in Russia and China in 1933, put the need for such an explanation this way:

> With the possible exception of the Equator, everything begins somewhere. Too many of those who write about their travels plunge straight in *medias res*; their opening sentence informs us bluntly and dramatically that the prow (or bow) of the dhow grated on the sand, and they stepped lightly ashore. No doubt they did. But why? With what excuse? What other and anterior steps had they taken? Was it boredom, business, or a broken heart that drove them so far afield? We have a right to know.
>
> **Peter Fleming**
> *One's Company (1934)*

In 2003, I wrote in the first edition of this book: "At the time of writing this introduction, the President of the United States, George W. Bush, has already rejected the Kyoto Agreement on the control of greenhouse gas emissions; European leaders appear to be in a dither and ecowarriors alongside anticapitalists have again clashed with riot police in the streets." A key change since then has been the Stern Review (Stern, 2006) on the economics of climate change. The likely environmental impact of climate change trajectories—rising sea levels permanently displacing millions of people, declining crop yields, more than a third of species facing extinction—had already been well rehearsed. What had not been adequately quantified and understood was the likely cost to the global economy (a 1% decline in economic output and 4% decline in consumption per head for every 1°C rise in average temperature) and that the cost of stabilizing the situation would cost about 1% of gross domestic product (GDP). It seemed not too much to pay, but attention is now firmly focused on the "credit crunch"' and the 2008 collapse of the financial sector. In the meantime, annual losses in natural capital worth from deforestation alone far exceed the losses of the current recession, severe as it is. Will it take ecological collapse to finally focus our attention on where it needs to be? This book has been written because, like most of its readers, I have a concern for the *quality of world* we live in, the urgent need for its maintenance and where necessary, its repair. In this book I set out what I believe is a key approach to problem solving and conflict resolution through the analysis and modeling of spatial phenomena. Whilst this book alone will perhaps not safeguard our world, you the reader on finishing this book will have much to contribute.

The phrase *quality of world* used above has been left intentionally broad, even ambiguous. It encompasses:

- Our natural environment—climate, soils, oceans, biological life (plants, animals, bacteria)—that can both nurture us and be hazards to us.
- The built environment that we have created to protect and house ourselves and to provide a modified infrastructure within which we can prosper.
- The economic environment that sustains our built environment and allows the organization of the means of production.
- The social, cultural, and legal environments within which we conduct ourselves and our interactions with others.

These environments are themselves diverse, continually evolving and having strong interdependence. Each of them varies spatially over the face of the globe mostly in a transition so that places nearer to each other are more likely to be similar than those farther apart. Some abrupt changes do, of course, happen, as, for example, between land and sea. They also change over time, again mostly gradually, but catastrophic events and revolutions do happen. Together they form a complex mosaic, the most direct visible manifestation being land cover and land use—our evolved cultural landscapes. Furthermore, the interaction of these different aspects of environment gives enormous complexity to the notion of "quality of life" for our transient existence on Earth. Globalization may have been a force for uniformity in business and consumerism, but even so businesses have had to learn to be spatially adaptive, so-called *glocalization*. When it comes to managing and ameliorating our world for a sustainable quality of life, there is no single goal, no single approach, no theory of it all. Let's not fight about it. Let us celebrate our differences and work toward a common language of understanding on how we (along with the rest of nature) are going to survive and thrive.

Metaphors of Nature

We often use metaphors as an aid in understanding complexity, none more so perhaps than in understanding nature and our relationship within it. These metaphors are inevitably bound up in philosophies of the environment, or knowledge of how the environment works and the technology available to us to modify/ameliorate our surrounding environment. Thus, for millennia, environmental knowledge was enshrined in folklore derived from the trial and error experiences of ancestors. Archaeology has revealed patterns of site selection that changed as we developed primitive technologies or adapted to new environments. Places for habitation had to satisfy the needs for water, food, raw materials, shelter, and safety, and humans learned to recognize those sites that offered the greatest potential for their mode of existence. Examples are numerous: caves near the feeding or watering places of animals; Neolithic cultivation of well-drained, easily worked river terraces; early fishing communities on raised beaches behind sheltered bays and so on. Undoubtedly mistakes were made and communities decimated, but those that survived learned to observe certain environmental truths or inevitabilities.

Successful early civilizations were those that had social structures that allowed them to best use or modify the landforms and processes of their physical environment. Thus, the Egyptians, Mesopotamians, and Sumerians devised irrigation systems to regulate and distribute seasonally fluctuating water supplies, while the Chinese and Japanese included widespread terracing as a means of increasing the amount of productive land. More than 2,500 years ago, the Chinese developed the Taoist doctrine of nature, in which the Earth and the sky had their own "way" or "rule" to maintaining harmony. Human beings should follow and respect nature's way or risk punishment in the form of disasters from land and sky. Thus, even at that time there were laws governing, for example, minimum mesh size on fishing nets so that fish would not be caught too young. Of course, our stewardship has not always been a continual upward journey of success. Some human civilizations have collapsed spectacularly through environmental impact and loss of natural resources (Tickell, 1993; Diamond, 2005). These disasters aside, the dominant metaphor was of "Mother Earth": a benevolent maker of life, a controlling parent that could provide for our needs, scold us when we erred, and, when necessary, put all things to right.

The industrial revolution allowed us to ratchet up the pace of development. Early warnings of the environmental consequences, such as from Marsh (1864), were largely ignored as the Victorians and their European and North American counterparts considered themselves above nature in the headlong rush to establish and exploit dominions. Our technologies have indeed allowed us to ameliorate our lifestyle and modify our environment on an unprecedented scale—on a global scale. But, from the 1960s, the cumulative effect of human impact on the environment and our increasing exposure to hazard finally crept onto the agenda and remains a central issue today. The rise of the environmental movement brought with it a new metaphor—Spaceship Earth—that was inspired by photos from the Apollo moon missions of a small blue globe rising above a desolate moonscape. We were dependant on a fragile life-support system with no escape, no prospect of rescue, if it were to irreparably break down. This coincided with the publication of seminal works, such as Rachel Carson's (1963) *Silent Spring*, which exposed the effects of indiscriminate use of chemical pesticides and insecticides;

McHarg's (1969) *Design with Nature,* which exhorted planners and designers to conform to and work within the capacity of nature rather than compete with it; and Schumacher's (1973) *Small Is Beautiful* proposed an economics that emphasized people rather than products and reduced the squandering of our "natural capital." The words *fractal, chaos, butterfly effect*, and *complexity* (Mandelbrot, 1983; Gleick, 1987; Lewin, 1993; Cohen and Stewart, 1994) have since been added to the popular environmental vocabulary to explain the underlying structure and workings of complex phenomena. Added to these is the *Gaia hypothesis* (Lovelock, 1988) in which the Earth is proposed to have a global physiology or may in fact be thought of as a superorganism capable of switching states to achieve its own goals in which we humans may well be (and probably are) dispensable organisms.

A Solution Space?

That we are capable of destroying our life support system is beyond doubt. As a species, we have already been responsible for a considerable number of environmental disasters. If I scan the chapter titles of Goudie's (1997) *The Human Impact Reader*, the list becomes long indeed, including (in no particular order): subsidence, sedimentation, salinization, soil erosion, desiccation, nutrient loss, nitrate pollution, acidification, deforestation, ozone depletion, climate change, wetland loss, habitat fragmentation, and desertification. I could go on to mention specific events, such as Exxon Valdez, Bhopal, and Chernobyl, but this book is not going to be a catalog of dire issues accompanied by finger-wagging exhortations that something must be done. Nevertheless, worrying headlines continue to appear, such as: "Just 100 months left to save the Earth" for a piece on how greenhouse gases may reach a critical level or tipping point beyond which global warming will accelerate out of control (Simms, 2008). One can be forgiven for having an air of pessimism; the environment and our ecosystems are definitely in trouble. But, we are far from empty-handed. We have a rich heritage of science and engineering, a profound knowledge of environmental processes and experience of conservation and restoration. The technologies that have allowed humankind to run out of control in its impact on the environment can surely be harnessed to allow us to live more wisely. Our ingenuity got us here and our ingenuity will have to get us out of it.

As stated above, we need a common language and, in this regard, we have some specific technologies—drawing upon science—that can facilitate this. While humankind has long striven to understand the workings of the environment, it has only been in the past 30 years or so that our data collection and data processing technologies have allowed us to reach a sufficiently detailed understanding of environmental processes so as to create *simulation* models. I would argue that it is only when we have reached the stage of successful quantitative simulation, can our level of understanding of processes allow us to confidently manage them. This is the importance of *environmental modeling*. Facilitated by this in a parallel development has been *environmental engineering*. Engineering also has a rich history, but while traditionally engineering has focused on the utilization of natural resources, environmental engineering has recently developed into a separate discipline that focuses on the impact and mitigation of environmental contaminants (Nazaroff and Alvarez-Cohen, 2001). While most management strategies arising out of environmental modeling will usually require some form of engineering response for implementation, environmental engineering provides solutions for managing water, air, and waste. Engineering in the title of this book refers to the need to design workable solutions; such designs are often informed by computational or simulation modeling. The youngest technology I would like to draw into this recipe for a common language is *geographic information systems* (GIS). Because environmental issues are inherently spatial—they occur somewhere, often affecting a geographic location or area—their spatial dimension needs to be captured if modeling and engineering are to be relevant in solving specific problems or avoiding future impacts. GIS have proved successful in the handling, integration, and analysis of spatial data and have become an easily accessible technology. While the link between simulation modeling and engineering has been longstanding, the link between GIS and these technologies is quite new, offers tremendous possibilities for improved environmental modeling and engineering solutions, and can help build these into versatile decision support systems for managing, even saving our environment. And that is why I have written this book.

Scope and Plan of This Book

From the early 1990s onwards, there has been an accelerating interest in the research and applications of GIS in the field of environmental modeling. There have been a few international conferences/workshops on the subject—most notably the series organized by the National Center for Geographic Information and Analysis (NCGIA), University of California, Santa Barbara in 1991, 1993, 1996, and 2000—and have resulted in a number of edited collections of papers (Goodchild et al., 1993; 1996; Haines-Young et al., 1993; NCGIA, 1996; 2000) as well as a growing number of papers in journals, such as the *International Journal of Geographical Information Science*, *Transactions in GIS*, *Hydrological Processes*, *Computers Environment and Urban Systems*, *ASCE Journal of Environmental Engineering*, *Photogrammetric Engineering and Remote Sensing*, *Computers and Geosciences,* and so on. But, working with GIS and environmental simulation models is not just a case of buying some hardware, some software, gathering some data, putting it all together and solving problems with the wisdom of a sage. While technology has simplified many things, there still remain many pitfalls, and users need to be able to think critically about what they are doing and the results that they get from the technology. Thus, the overall aim of this book is to provide a structured, coherent text that not only introduces the subject matter, but also guides the reader through a number of specific issues necessary for critical usage. This book is aimed at final-year undergraduates, postgraduates, and professional practitioners in a range of disciplines from the natural sciences, social sciences to engineering, at whatever stage in their lifelong learning or career they need or would like to start working with GIS and environmental models. The focus is on the use of these two areas of technology in tandem and the issues that arise in so doing. This book is less concerned with the practicalities of software development and the writing of code (e.g., Payne, 1982; Kirkby et al., 1987; Hardisty et al., 1993; Deaton and Winebrake, 2000; Wood, 2002). Nor does it consider in detail data collection technologies, such as remote sensing, GPS, data loggers, and so on, as there are numerous texts that already cover this ground (e.g., Anderson and Mikhail, 1998; Skidmore, 2002).

The overall thrust of this book can be summarized in the mapping:

$$f\colon \Omega \rightarrow \Re \tag{1.1}$$

where Ω = set of domain inputs, $\Re$ = set of real decisions. In other words, all decisions (including the decision not to make a decision) should be adequately evidenced using appropriate sources of information. This is perhaps stating the obvious, but how often, in fact, is there insufficient information, a hunch, or a gut feeling? GIS, environmental modeling, and engineering are an approach to generating robust information upon which to make decisions about complex spatial issues.

The subject matter is laid out in three sections. Section I concentrates uniquely on GIS: what they are, how data are structured, what are the most common types of functionality. GIS will be viewed from the perspective of a technology, the evolution of its scientific basis, and, latterly, its synergies with other technologies within a geocomputational paradigm. This is not intended to be an exhaustive introduction as there are now many textbooks that do this (e.g., Chrisman, 1997; Burrough and McDonnell, 1998; Longley et al., 2005; Heywood et al., 2006) as well as edited handbooks (e.g., Wilson and Fotheringham, 2008). Rather, its purpose is to lay a sufficient foundation of GIS for an understanding of the substantive issues raised in Section III. Section II similarly focuses on modeling both from a neutral scientific perspective of its role in simulating and understanding phenomena and from a more specific perspective of environmental science and engineering. Section III is by far the largest. It looks at how GIS and simulation modeling are brought together, each adding strength to the other. There are examples of case studies and chapters covering specific issues, such as interoperability, data quality, model validity, space-time dynamics, and decision-support systems. Those readers who already have a substantial knowledge of GIS or have completed undergraduate studies in GIS may wish to skip much of Section I and move quickly to Sections II and III. Those readers from a simulation modeling background in environmental science or engineering should read Section I, skim through Section II, and proceed to Section III. In a book such as this, it is always possible to write more about any one topic; there are always additional topics that a reader might consider should be added. There are, for example, as many environmental models as there are aspects of the environment. GIS, environmental modeling, and engineering are quite endless and are themselves evolving. Also, I have tried not to focus on any one application of simulation modeling. Given its popularity, there is a temptation to focus on GIS and hydrology, but that would detract from the overall purpose of this book, which is to focus on generic issues of using GIS and external simulation models to solve real problems. Presented in the following chapters is what I consider to be a necessary understanding for critical thinking in the usage of such systems and their analytical outputs. Enjoy.

Section I

2

From GIS to Geocomputation

The cosmological event of the Big Bang created the universe and in so doing space–time emerged (some would say "switched on") as an integral aspect of gravitational fields. Space and time are closely interwoven and should more properly be thought of as a four-dimensional (4D) continuum in which time and space, over short durations, are interchangeable. Nevertheless, we conventionally think of separate one-dimensional (1D) time and three-dimensional (3D) space. The terrestrial space on which we live, the Earth, is at least 4.5 billion years old and has been around for about 40% of the time since time began. Since our earliest prehistory, we have grappled with the problems of accurately measuring time and space. Crude measures of time probably came first given the influences of the regular cycles of the day, tides, the moon, and seasons on our lives as we evolved from forager to agriculturist. With technology, we have produced the atomic clock and the quartz watch. Measuring position, distances, and area were less obvious in the absence of the type of benchmark that the natural cycles provided for time. Early measurements used a range of arbitrary devices—the pace, the pole, the chain—and longer distances tended to be equated with the time it took to get to destinations. Much later, the development of accurate clocks was the key to solving the problem of determining longitudinal position when coupled with observations of the sun. Measurement requires numerical systems, and 1D time requires either a linear accumulation (e.g., age) or a cyclical looping (e.g., time of day). Measurement of 3D space requires the development of higher order numerical systems to include geometry and trigonometry. Let us not forget that at the root of algebra and the use of algorithms was the need for precise partitioning of space (land) prescribed by Islamic law on inheritance. Calculus was developed with regard to the changing position (in time) of objects in space as a consequence of the forces acting upon them.

Three fundamental aspects of determining position are: a datum, a coordinate system (both incorporating units of measurement), and an adequate representation of the curved (or somewhat crumpled) surface of the Earth in the two dimensions of a map, plan, or screen. The establishment of a datum and coordinate system is rooted in geodetic surveying, which aims to precisely determine the shape and area of the Earth or a portion of it through the establishment of wide-area triangular networks by which unknown locations can be tied into known locations. Cartographers aim to represent geographic features and their relationships on a plane. This involves both the *art* of reduction, interpretation, and communication of geographic features and the *science* of transforming coordinates from the spherical to a plane through the construction and utilization of map projections. The production of quality spatial data used to be a time-consuming, expensive task and for much of the twentieth century there was a spatial data "bottleneck" that held back the wider use of such data. Technology has provided solutions in the form of the global positioning system (GPS), electronic total stations, remote sensing (RS), digital photogrammetry, and geographic information systems (GIS). GPS, RS, and GIS are now accessible to every citizen through inexpensive devices and the Internet. Determining where is no longer difficult and, through mobile devices such as GPS-enabled smartphones, determining one's geographic position and location has become no more difficult than telling the time.

This chapter will chart the rise of the GIS as a *technology*, consider its main paradigms for representing the features of the Earth and structuring data about them. The basic functionality of GIS will be described with examples. A "systems" view of GIS will then be developed bringing us to the point where GIS can be formally defined. The limitations of modern GIS will be discussed leading us to consider the rise of geocomputation as a new paradigm and the role of GIS within it.

In the Beginning ...

It would be nice to point to a date, a place, an individual and say, "That's where it all started, that's the father of GIS." But no. As Coppock and Rhind put it in their article on the History of GIS (1991), "unhappily, we scarcely know." In the beginning, of course, there were no GIS "experts" and nobody specifically set out to develop a new body of technology nor a new scientific discipline for that matter. In the mid-1960s, there were professionals from a range of disciplines, not many and mostly in North America, who were excited by the prospect of handling spatial data digitally. There were three main focal points: the Harvard Graduate School of Design, the Canada Land Inventory, and the U.S. Census Bureau. In each of these organizations were small groups of pioneers who made important contributions toward laying the foundations for today's GIS industry.

The significance of the Harvard Graduate School of Design lies in its Laboratory for Computer Graphics and Spatial Analysis, a mapping package called SYMAP (1964), two prototype GIS, called GRID (1967), and ODYSSEY (c. 1978), and a group of talented individuals within the laboratory and the wider graduate school: N. Chrisman, J. Dangermond, H. Fisher, C. Steinitz, D. Sinton, T. Peucker, and W. Warntz, to name a few. The creator of SYMAP was Howard Fisher, an architect. His use of line printers to produce three types of map—isoline, choropleth, and proximal—was a

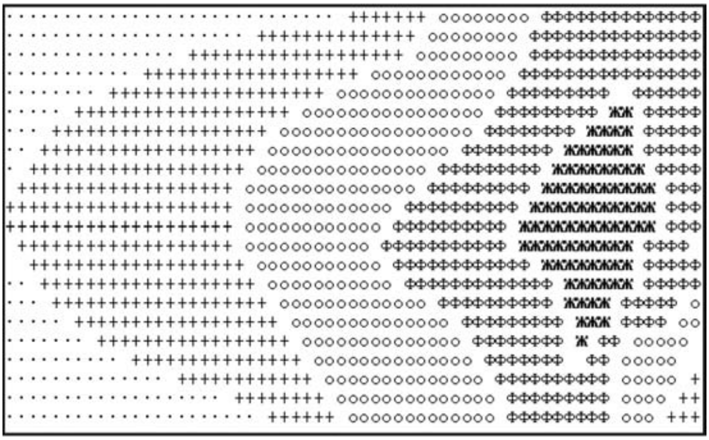

FIGURE 2.1
Sample of a SYMAP-type line printer contour map showing emphasis on similarities. The contour lines are perceived only through the "gap" between the areas of printed symbols.

way of visualizing or recognizing spatial similarities or groupings in human and physical phenomena (McHaffie, 2000). The other leap was a recognition (rightly or wrongly) that just about any such phenomenon, no matter how ephemeral or whether described quantitatively or qualitatively could be represented as a map of surfaces or regions. The printing of these maps using equally spaced characters or symbols, line by line, naturally resulted in a "blocky," cell-based map representation (Figure 2.1). David Sinton, a landscape architect, took cell-based (raster) mapping forward with GRID, which allowed analyses to include several thematic data sets (layers) for a given area. Furthermore, by 1971 a rewrite of GRID allowed users to define their own logical analyses rather than being restricted to a limited set of prepackaged procedures. Thus, a flexible user interface had been developed. By the late 1970s, ODYSSEY, a line-based (vector) GIS prototype had been written capable of polygon overlay. In this way, it can be seen that the overlay or co-analysis of several thematic layers occupied the heart of early GIS software strategies (Chrisman, 1997).

In 1966, the Canada Geographic Information System (CGIS) was initiated to serve the needs of the Canada Land Inventory to map current land uses and the capability of these areas for agriculture, forestry, wildlife, and recreation (Tomlinson, 1984). Tomlinson had recognized some years earlier that the manual map analysis tasks necessary for such an inventory over such a large area would be prohibitively expensive and that a technological solution was necessary. Within this solution came a number of key developments: optical scanning of maps, raster to vector conversion, a spatial database management system, and a seamless coverage that was nevertheless spatially partitioned into "tiles." The system was not fully operational until 1971, but has subsequently grown to become a digital archive of some 10,000 maps (Coppock and Rhind, 1991).

The significance of the U.S. Bureau of Census in developing its Dual Independent Map Encoding (DIME) scheme in the late 1960s is an early example of inserting additional information on spatial relationships into data files through the use of topological encoding. Early digital mapping data sets had been unstructured collections of lines that simply needed to be plotted with the correct symbology for a comprehensible map to emerge. But the demands for analysis of map layers in GIS required a structuring that would allow the encoding of area features (polygons) from lines and their points of intersection, ease identification of neighboring features, and facilitate the checking of internal consistency. Thus, DIME was a method of describing urban structure, for the purposes of census, by encoding the topological relationships of streets, their intersection points at junctions and the street blocks and census tracts that the streets define as area features. The data structure also provided an automated method of checking the consistency and completeness of the street block features (U.S. Bureau of Census, 1970). This laid the foundation of applying topology or graph theory now common in vector GIS.

Technological Facilitation

The rise of GIS cannot be separated from the developments in information and communication technology that have occurred since the 1960s. A timeline illustrating developments in GIS in relation to background formative events in technology and other context is given in Table 2.1. Most students and working professionals today are familiar at least with the PC or Mac. I am writing the second edition of this book in 2008/09 on a notebook PC (1.2 GHz CPU, 1 GB RAM, 100 GB disk, wireless and Bluetooth connectivity) no bigger or thicker than an A4 pad of paper. My GIS and environmental modeling workhorse is an IBM M Pro Intellistation (dual CPU 3.4 GHz each, 3.25 GB RAM, 100 GB disk). They both run the same software with a high degree of interoperability, and they both have the same look and feel with toolbars, icons, and pull-down menus. Everything is at a click of a mouse. I can easily transfer files from one to the other (also share them with colleagues) and I can look up just about anything on the Internet. Even my junk mail has been arriving on CD and DVD, so cheap and ubiquitous has this medium become, and USB data sticks are routinely given away at conferences and exhibitions. It all takes very little training and most of the basic functions have become intuitive. I'm tempted to flex my muscles (well, perhaps just exercise my index finger) for just a few minutes on the GIS in this laptop … and have indeed produced Figure 2.2—a stark contrast to Figure 2.1.

TABLE 2.1

Timeline of Developments in GIS in Relation to Background Formative Events in Technology and Other Context

Year	GIS	Context	
1962		Carson's *Silent Spring*	
1963	Canadian Geographic Information System		
1964	Harvard Lab for Computer Graphics & Spatial Analysis	GPS specification	
1966	SYMAP	WGS-66	
1967	U.S. Bureau of Census DIME		
1968		Relational database defined by Codd	
1969	ESRI, Intergraph, Laser-Scan founded	Man on the noon; NEPA; McHarg's *Design with Nature*	
1970	Acronym GIS born at IGU/UNESCO conference	Integrated circuit	
1971		ERTS/Landsat 1 launched	
1973	U.K. Ordnance Survey starts digitizing		
1974	AutoCarto conference series; *Computers & Geosciences*	UNIX	
1975		C++; SQL	
1978	ERDAS founded	First GPS satellite launched	
1980	FEMA integrates USGS 1:2 m mapping into seamless database		
1981	*Computers, Environment & Urban Systems*; Arc/Info launched	8088 chip; IBM PC	
1983		Mandelbrot's *The Fractal Geometry of Nature*	
1984	1st Spatial Data Handling Symposium	80286 chip, RISC chip; WGS-84	
1985		GPS operational	
1986	Burrough's *Principles of Geographical Information Systems for Land Resources Assessment*; MapInfo founded	SPOT 1 launched	
1987	*International Journal of Geographical Information Systems*; GIS/LIS conference series; *"Chorley" Report*	80386 chip	Internet; mobile phones
1988	NCGIA; *GIS World*, U.K. RRL initiative	Berlin Wall comes down	
1989	U.K. Association for Geographic Information		
1990		Berners–Lees launches WWW	
1991	USGS digital topo series complete 1st International Symposium on Integrating GIS and Environmental Modeling	Dissolution of Soviet Union	
1992		Rio Earth Summit – Agenda 21	
1993	GIS Research U.K. conference series	Pentium chip; full GPS constellation	
1994	Open GIS Consortium	HTML	

Continued

TABLE 2.1 (*Continued*)

Timeline of Developments in GIS in Relation to Background Formative Events in Technology and Other Context

Year	GIS	Context
1995	OS finished digitizing 230,000 maps	Java
1996	1st International Conference on GeoComputation; *Transactions in GIS*	
1997	*IJGIS* changes "*Systems*" to "*Science*"; last AutoCarto; *Geographical and Environmental Modeling*	Kyoto Agreement on CO_2 reduction
1998	*Journal of Geographical Systems*; last GIS/LIS	GPS selective availability off
2000		"Millennium Bug"
2003	1st ed.: *GIS, Environmental Modeling & Engineering*	
2005	Google Maps; Google Earth	
2006		*Stern Review: The economics of climate change*
2008	Google Street View	

To fully comprehend the technological gulf we have crossed, let me briefly review a late 1970s GIS-based land capability study in South Dakota (Schlesinger et al., 1979). The project was carried out on an IBM 370/145 mainframe computer using 10 standalone program modules written in FORTRAN IV and IBM Assembler. A digitizing tablet and graphics terminal were available, but all hardcopy maps were produced using a line printer. Maps wider than a 132-character strip had to be printed and glued together. The study area covered 115 km^2; size of cell was standardized at one acre (~0.4 ha). With the objective to identify land use potential, four base data layers were digitized: 1969 and 1976 land use from aerial photographic interpretation (API), soils, and underlying geology from published map sheets. Through a process

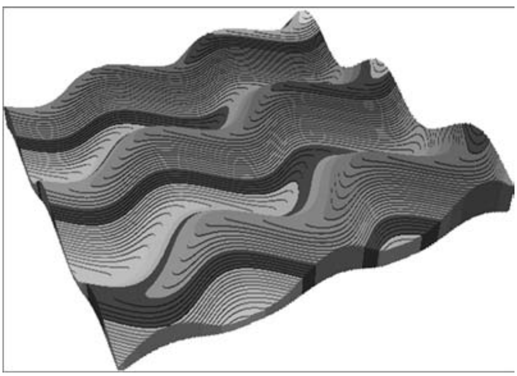

FIGURE 2.2
Laptop GIS of today: 3-D topographic perspective of a landscape.

TABLE 2.2

Multiple Layer Production from Three Source Data Sets

Base Maps → **↓ Factor Maps**	**1969** **Land Use**	**1976** **Land Use**	**Soils**	**Geology**
Slope			✓	
Flood hazards			✓	
Potential for building sites			✓	
Potential for woodland wildlife habitat			✓	
Potential for rangeland habitat			✓	
Potential for open land habitat			✓	
Limitations to road and street construction			✓	
Limitations for septic tank absorption fields			✓	
Soils of statewide importance for farmland			✓	
Sliding hazards				✓
Groundwater recharge areas				✓
Land use change	✓	✓		
Limitations to sewage lagoons			✓	✓
Important farmland		✓	✓	
Important farmland lost to urban development	✓	✓	✓	
Limitations to urban development			✓	✓
Land suitable for urban development, but not important agricultural land			✓	✓
Limitations for septic tanks	✓	✓	✓	
Limitations for new urban development	✓	✓	✓	✓

Source: Based on Schlesinger, J., Ripple, W., and Loveland, T.R. (1979) *Harvard Library of Computer Graphics* 4: 105–114.

of either reclassification of single layers or a logical combination (overlay) of two or more layers with reclassification, a total of 19 new factor maps were created (Table 2.2) to answer a range of spatial questions where certain characteristics are concerning land suitability for development. Typical of the many pioneering efforts of the time, this study achieved its goals and was well received in the community despite the rudimentary hardware and software tools available.

Some of the changes are obvious. Over the intervening 30 years, the action of Moore's Law, by which the hardware price to performance ratio is expected to double every 18 months, means that the laptop I'm writing on far outstrips the IBM mainframe of that time in terms of power, performance, and storage by several orders of magnitude at a fraction of the cost in real terms. Instead of using a collection of software modules that may need to be modified and recompiled to satisfy the needs of the individual project, we have a choice of off-the-shelf packages (e.g., MapInfo, ArcGIS) that combine a wide range of functionality with mouse- and icon/menu-driven interfaces. For project-specific needs, most of these packages have object-oriented scripting languages

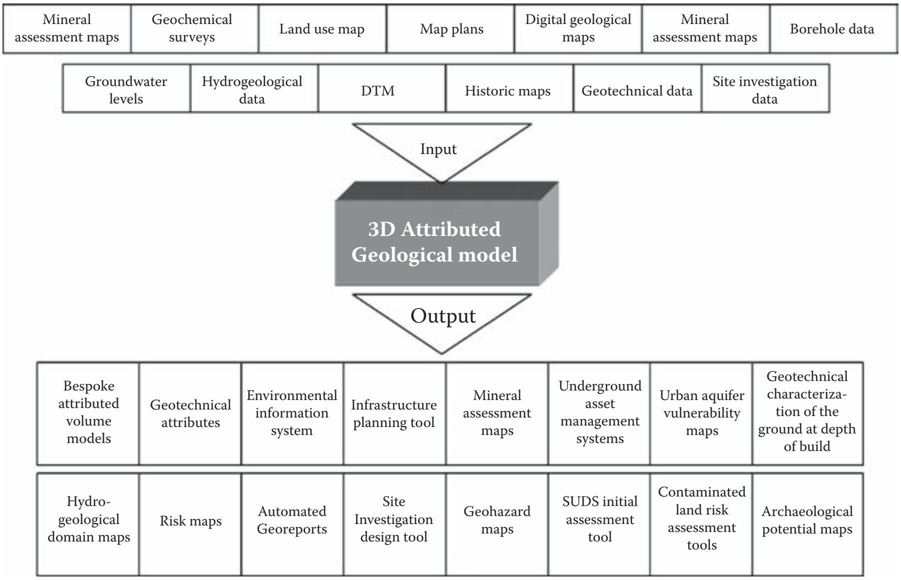

FIGURE 2.3
A contemporary geological application using spatial modeling tools. (Adapted from Royse, K.R., Rutter, H.K., and Entwisle, D.C. (2009) *Bulletin of Engineering Geology and the Environment* 68: 1–16.)

that facilitate customization and the addition of new functionality with many such scripts available over the Internet. Moreover, analysis can now be vastly extended to include external computational models that communicate either through the scripting or use of common data storage formats. Although the availability of digital map data is uneven across the world, particularly when it comes to large-scale mapping, off-the-shelf digital data ready for use in GIS are much more common today to the point where, certainly for projects in North America and Europe, there is hardly the need anymore to manually digitize. As mentioned above, the bottleneck in the production of digital spatial data has been burst not only by technologies, such as GPS, RS, and digital photogrammetry, but through palm-top data loggers, high-speed scanners, digital data transfer standards, and, above all, the computer capacity to cost-effectively store, index, and deliver huge data sets. In contrast to Table 2.2 in which only four data sources were used, Figure 2.3 summarizes the many input sources and output derivative data sets designed by the British Geological Survey in a recent project to build an integrate 3D geological and hydrogeological model. This model is to support development in the Thames Gateway, U.K., which at the time of writing is Europe's largest regeneration program. Nevertheless, despite the technological advancement that has made spatial tools and particular GIS more widespread, sophisticated, and easier to use, many of the underlying principles have remained largely the same.

FIGURE 2.4
A view of a sample landscape. (Photo courtesy of the author.)

Representing Spatial Phenomena in GIS

The dominant paradigm in the way GIS data are structured comes from the idea that studies of landscape (both human and physical) and the solution to problems concerning the appropriate use of land can be achieved by describing the landscape as a series of relevant factor maps or layers that can then be overlaid to find those areas having particular combinations of factors that would identify them as most suited to a particular activity. The methodology in its modern GIS context derives from the seminal work of McHarg (1969) as well as the conventional cartographic tradition of representing spatial phenomena. Although the use of manual overlay of factor maps considerably predates McHarg (Steinitz et al., 1976), he provided a compelling case for the methodology as a means of organizing, analyzing, and visualizing multiple landscape factors within a problem-solving framework. Consider the landscape shown in Figure 2.4.

This landscape can be viewed both holistically as a piece of scenery and as a series of constituent elements, such as its topography, geology, hydrology, slope processes, flora, fauna, climate, and manmade (anthropomorphic) features, to name but a number that could be separated out. At any place within this landscape there are several or all constituents to be considered: stand on any point and it has its topography, geology, hydrology, microclimate, and so on. Any comprehensive map of all these constituents would quickly become cluttered and complex—almost impossible to work with. So, consider then the mapped constituents of a very similar landscape in Figure 2.5(a–i).

Although this particular landscape has been artificially created to demonstrate a number of issues throughout this book, it illustrates well a number of aspects of the layer or coverage paradigm and the graphic primitives used in any one layer. First, in order for a selection of layers to be used together, superimposed and viewed as a composite, *they must all conform to the same coordinate system and map projection*. This is critically important, otherwise the layers will be distorted and wrongly positioned in relation to one another. Individual layers, however, need not necessarily cover exactly the same area of the landscape in their extent as may happen, for example, if they have been derived from different surveys or source documents. Each layer can nevertheless be clipped to a specific study area as has happened in Figure 2.5. Second, some of the layers are given to represent *discrete objects* in the landscape (e.g., landslides, streams, land cover parcels) while others represent a *continuous field* (e.g., topography, gradient, rainfall), which varies in its value across the landscape. What aspects of the landscape should be treated as continuous or discrete and how they should be presented cartographically is an old, but significant problem, which can still be debated today (Robinson and Sale, 1969; Peuquet, 1984; Goodchild, 1992a; Burrough, 1992; Burrough and Frank 1996; Spiekermann and Wegener, 2000; Goodchild et al., 2007). To a considerable extent, it is a matter of data resolution, scale of representation, convention, and convenience. For example, landslides can be quickly mapped at a regional level as individual points representing each scar in the terrain (as in Figures 2.5(h) and 2.6(a)). Another approach would be to represent each landslide as a line starting at the scarp and tracing the down slope extent of the debris to the toe (Figure 2.6(b)). Clearly any laterally extensive landslide in Figure 2.5(h) would represent a methodological problem for which a single point or a line would be an oversimplification. So, yet another approach would be to represent either the whole landslide or its morphological elements according to a consistent scheme (e.g., source, transport, deposition) as polygons (Figure 2.6(c)). This latter approach, while providing more information, is more time consuming and expensive to produce. Finally, these landslides could be represented as a field of varying numbers of landslides within a tessellation of cells (Figure 2.6(d)), or as densities (Figure 5.11(a)).

To pursue this issue just a bit further, topography is a continuous field, but is conventionally represented by contours that in geometric terms are nested polygons. Gradient on the other hand is also a continuous field, but would generally be confusing to interpret if drawn as contours and, thus, is usually represented by a tessellation of cells, each having its own gradient value. Soils are conventionally classified into types and each type is represented

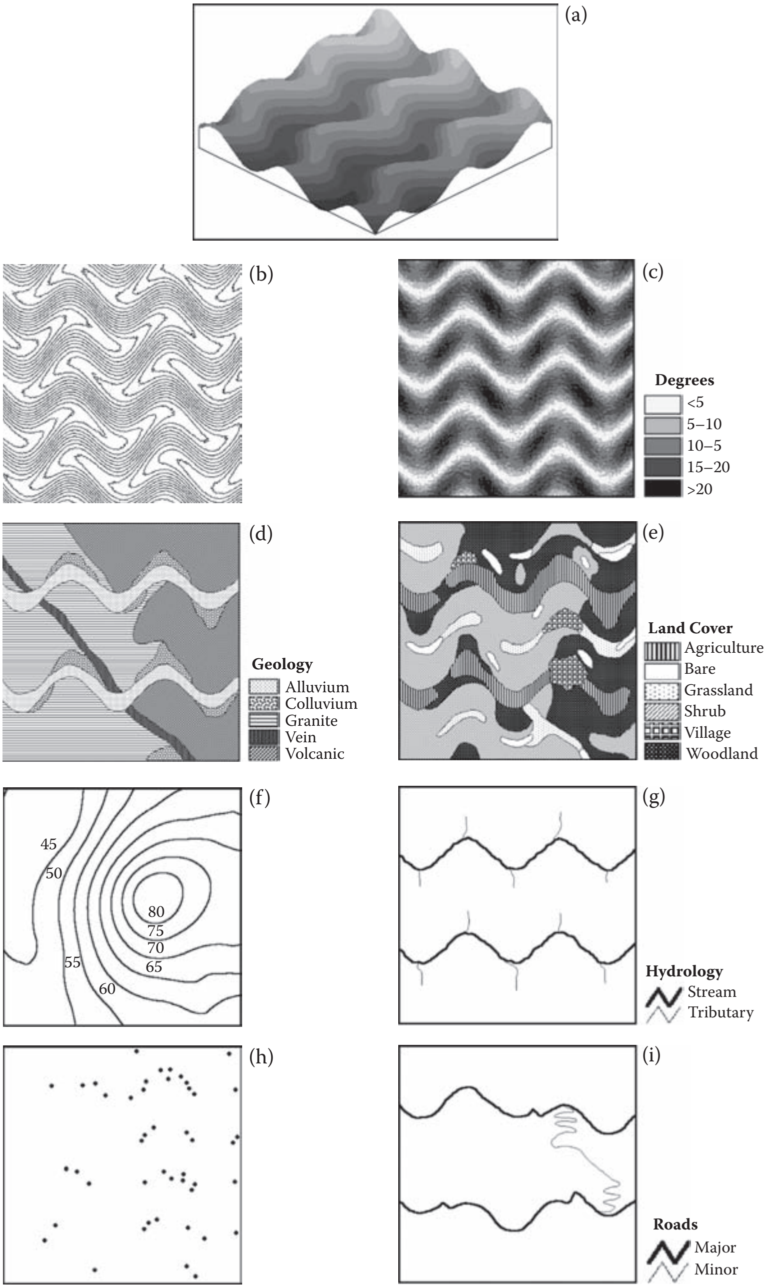

FIGURE 2.5
Mapped constituents of an example landscape in eight layers (coverages): (a) oblique view of topography, (b) contours, (c) slope gradient, (d) geology, (e) land cover, (f) rainfall isohyets from a storm event, (g) drainage network, (h) landslide scars, (i) transport.