

Ninth Edition

Introduction to

GEOGRAPHIC INFORMATION SYSTEMS

KANG-TSUNG CHANG



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Ninth Edition

INTRODUCTION TO GEOGRAPHIC INFORMATION SYSTEMS

Kang-tsung Chang

University of Idaho





INTRODUCTION TO GEOGRAPHIC INFORMATION SYSTEMS, NINTH EDITION

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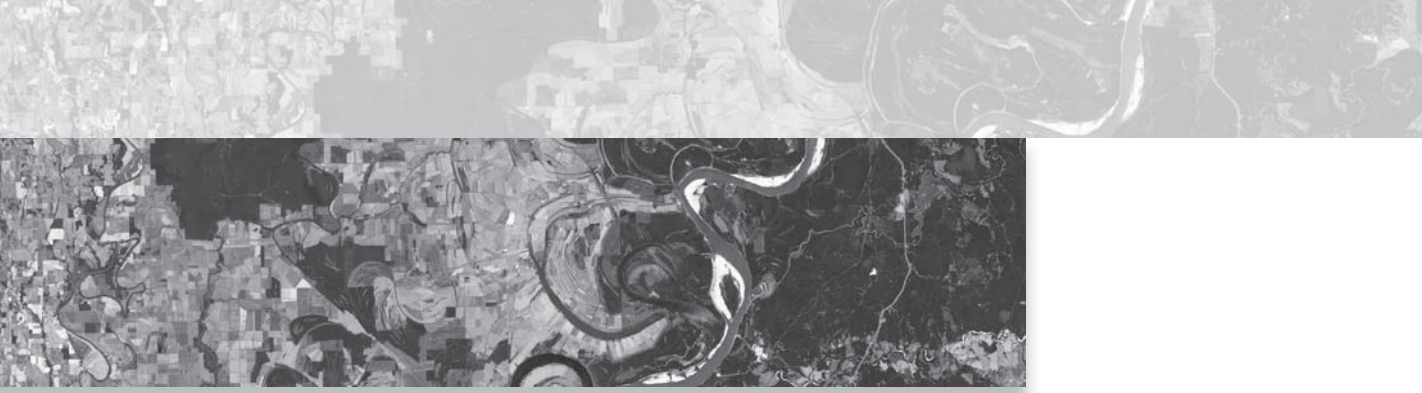
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PREFACE

ABOUT GIS

A geographic information system (GIS) is a computer system for storing, managing, analyzing, and displaying geospatial data. Since the 1970s GIS has been important for professionals in natural resource management, land use planning, natural hazards, transportation, health care, public services, market area analysis, and urban planning. It has also become a necessary tool for government agencies of all the levels for routine operations. More recent integration of GIS with the Internet, global positioning system (GPS), wireless technology, and Web service has found applications in location-based services, Web mapping, in-vehicle navigation systems, collaborative Web mapping, and volunteered geographic information. It is therefore no surprise that geospatial technology was chosen by the U.S. Department of Labor as a high-growth industry. Geospatial technology centers on GIS and uses GIS to integrate data from remote sensing, GPS, cartography, and surveying to produce useful geographic information.

Many of us, in fact, use geospatial technology on a daily basis. To locate a restaurant, we go online, type the name of the restaurant, and find it on a location map. To make a map for a project, we go to Google Maps, locate a reference map, and superimpose our own contents and symbols to complete the map. To find the shortest route for driving, we

use an in-vehicle navigation system to get the directions. And, to record places we have visited, we use geotagged photographs. All of these activities involve the use of geospatial technology, even though we may not be aware of it.

It is, however, easier to be GIS users than GIS professionals. To become GIS professionals, we must be familiar with the technology as well as the basic concepts that drive the technology. Otherwise, it can easily lead to the misuse or misinterpretation of geospatial information. This book is designed to provide students with a solid foundation in GIS concepts and practice.

UPDATES TO THE NINTH EDITION

The ninth edition covers GIS concepts, operations, and analyses in 18 chapters. Chapters 1 to 4 explain GIS concepts and vector and raster data models. Chapters 5 to 8 cover geospatial data acquisition, editing, and management. Chapters 9 and 10 include data display and exploration. Chapters 11 and 12 provide an overview of core data analysis. Chapters 13 to 15 focus on surface mapping and analysis. Chapters 16 and 17 examine linear features and movement. And Chapter 18 presents GIS models and modeling. Designed to meet the needs of students from different disciplines, this book can be used in a first or second GIS course.

Instructors may follow the chapters in sequence. They may also reorganize the chapters to suit their course needs. As an example, exercises on geometric transformation (Chapter 6) and topological editing (Chapter 7) require standard or advanced license levels of ArcGIS, and they can perhaps be covered in a second GIS course. On the other hand, geocoding (Chapter 16) is a topic familiar to many students and can be introduced early as an application of GIS.

The revision of the ninth edition has focused on three areas: new developments in GIS, changes in acquisition of geospatial data, and careful interpretation of important GIS concepts. New developments in GIS include open source and free GIS, integration of GIS with Web2.0 and mobile technology, new horizontal datums, animated maps, quality of geocoding, and regression analysis with spatial data. Acquisition of free geospatial data, such as very high resolution satellite images, LiDAR data, LiDAR-based DEMs, and global-scale data, is now possible from websites maintained by the U.S. Geological Survey, National Aeronautics and Space Administration, and other organizations. Basic concepts, such as datum shift, topology, spatial database, spatial join, and map algebra, are closely linked to GIS operations and analyses and must be firmly grasped by beginning GIS users. The revision of the ninth edition covers every chapter.

This ninth edition continues to emphasize the practice of GIS. Each chapter has problem-solving tasks in the applications section, complete with data sets and instructions. With the addition of four new tasks in Chapters 2, 11, 12, and 13, the number of tasks in the new edition totals 87, with two to seven tasks in each chapter. The instructions for performing the tasks correlate to ArcGIS 10.5. All tasks in this edition use ArcGIS and its extensions of Spatial

Analyst, 3D Analyst, Geostatistical Analyst, Network Analyst, and ArcScan. In addition, a challenge task is found at the end of each applications section.

The ninth edition retains task-related questions and review questions, which have proved to be useful to readers of the earlier editions. Finally, references and websites have been updated in this edition.

The website for the ninth edition, located at www.mhhe.com/changgis9e, contains a password-protected instructor's manual. Contact your McGraw-Hill sales representative for a user ID and password.

CREDITS

Data sets downloaded from the following websites are used for some tasks in this book:

Montana GIS Data Clearinghouse

<http://nris.mt.gov/gis/>

Northern California Earthquake Data

<http://quake.geo.berkeley.edu/>

University of Idaho Library

<http://inside.uidaho.edu>

Washington State Department of Transportation
GIS Data

[http://www.wsdot.wa.gov/mapsdata/
geodatacatalog/default.htm](http://www.wsdot.wa.gov/mapsdata/geodatacatalog/default.htm)

Wyoming Geospatial Hub

<http://geospatialhub.org/>

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Kang-tsung Chang

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INTRODUCTION

CHAPTER OUTLINE

- 1.1 GIS
- 1.2 Elements of GIS
- 1.3 Applications of GIS
- 1.4 Integration of GIS, Web2.0, and Mobile Technology
- 1.5 Organization of This Book
- 1.6 Concepts and Practice

A **geographic information system (GIS)** is a computer system for capturing, storing, querying, analyzing, and displaying geospatial data. One of many applications of GIS is disaster management.

On March 11, 2011, a magnitude 9.0 earthquake struck off the east coast of Japan, registering as the most powerful earthquake to hit Japan on record. The earthquake triggered powerful tsunami waves that reportedly reached heights of up to 40 meters and traveled up to 10 kilometers inland. In the aftermath of the earthquake and tsunami, GIS played an important role in helping responders and emergency managers to conduct rescue operations, map severely damaged areas and infrastructure, prioritize medical needs, and locate

temporary shelters. GIS was also linked with social media such as Twitter, YouTube, and Flickr so that people could follow events in near real time and view map overlays of streets, satellite imagery, and topography. In September 2011, the University of Tokyo organized a special session on GIS and Great East Japan Earthquake and Tsunami in the Spatial Thinking and GIS international conference for sharing information on the role of GIS in managing such a disaster.

Hurricane Irene formed over the warm water of the Caribbean on August 21, 2011, and in the following week, it moved along a path through the United States East Coast and as far north as Atlantic Canada. Unlike the Great East Japan

Earthquake, which happened so quickly, Hurricane Irene allowed government agencies and organizations to develop GIS data sets, applications, and analysis before it arrived in their areas. Online hurricane trackers were set up by news media such as MSNBC and CNN, as well as by companies such as Esri and Yahoo. And GIS data resources were provided by the National Oceanic and Atmospheric Administration (NOAA) on forecast track, wind field, wind speed, and storm surge, and by the Federal Emergency Management Agency (FEMA) on disaster response and recovery efforts. Although severe flooding was reported in upstate New York and Vermont, the preparation helped reduce the extent of damage by Hurricane Irene.

For both the Great East Japan Earthquake and Hurricane Irene, GIS played an essential role in integrating data from different sources to provide geographic information that proved to be critical

for relief operations. GIS is the core of geospatial technology, which is related to a number of fields including remote sensing, Global Positioning System (GPS), cartography, surveying, geostatistics, Web mapping, programming, database management, and graphics design. For many years, geospatial technology has been considered a high growth job sector in the United States, with substantial numbers of new jobs projected in GIS and its related fields.

1.1 GIS

Geospatial data describe both the locations and characteristics of spatial features. To describe a road, for example, we refer to its location (i.e., where it is) and its characteristics (e.g., length, name, speed limit, and direction), as shown in Figure 1.1. The ability of a GIS to handle and process geospatial

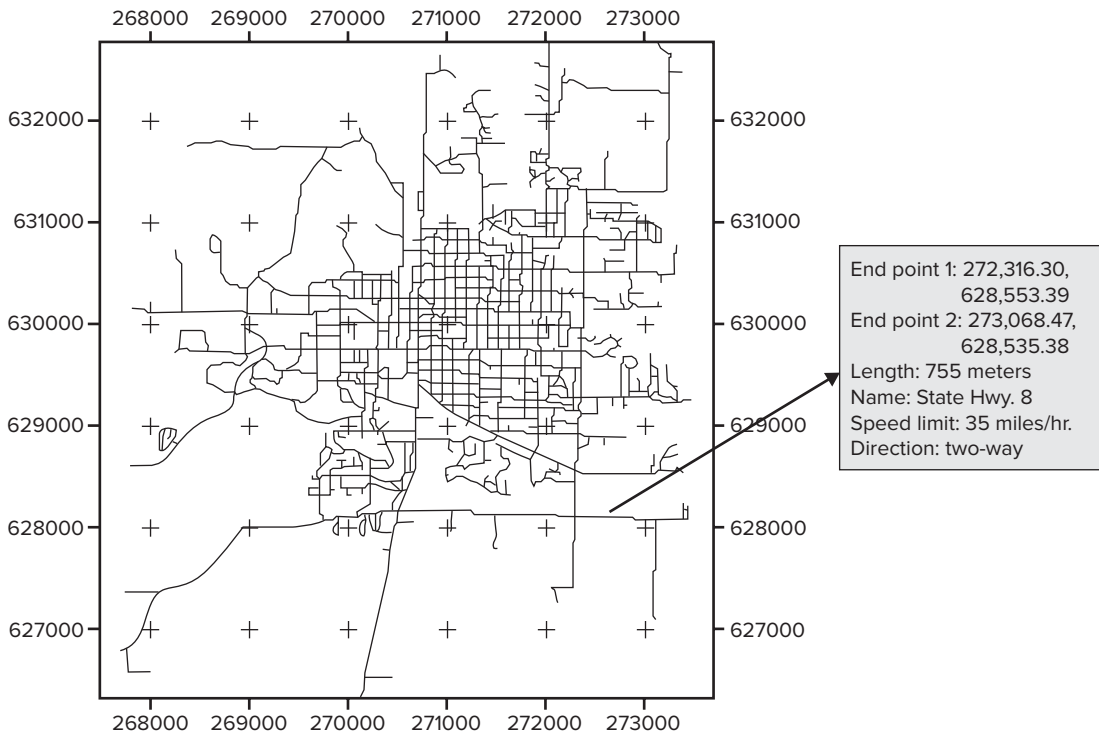


Figure 1.1

An example of geospatial data. The street network is based on a plane coordinate system. The box on the right lists the x - and y -coordinates of the end points and other attributes of a street segment.

data distinguishes GIS from other information systems and allows GIS to be used for integration of geospatial data and other data.

1.1.1 Components of a GIS

Similar to other information technologies, a GIS requires the following components besides geospatial data:

- **Hardware.** GIS hardware includes computers for data processing, data storage, and input/output; printers and plotters for reports and hard-copy maps; digitizers and scanners for digitization of spatial data; and GPS and mobile devices for fieldwork.
- **Software.** GIS software, either commercial or open source, includes programs and applications to be executed by a computer for data management, data analysis, data display, and other tasks. Additional applications, written in Python, JavaScript, VB.NET, or C++, may be used in GIS for specific data analyses. Common user interfaces to these programs and applications are menus, icons, and command lines, using an operating system such as Windows, Mac, or Linux.
- **People.** GIS professionals define the purpose and objectives for using GIS and interpret and present the results.
- **Organization.** GIS operations exist within an organizational environment; therefore, they must be integrated into the culture and decision-making processes of the organization for such matters as the role and value of GIS, GIS training, data collection and dissemination, and data standards.

1.1.2 A Brief History of GIS

The origins of GIS in its present form lie in the application of rapidly developing computing tools, especially computer graphics in a variety of fields such as urban planning, land management, and geocoding in the 1960s and 1970s. The first operational GIS is reported to have been developed by Roger Tomlinson in the early 1960s for storing,

manipulating, and analyzing data collected for the Canada Land Inventory (Tomlinson 1984). In 1964, Howard Fisher founded the Harvard Laboratory for Computer Graphics, where several well-known computer programs of the past such as SYMAP, SYMVU, GRID, and ODESSEY were developed and distributed throughout the 1970s (Chrisman 1988). These earlier programs were run on mainframes and minicomputers, and maps were made on line printers and pen plotters. In the United Kingdom, computer mapping and spatial analysis were also introduced at the University of Edinburgh and the Experimental Cartography Unit (Coppock 1988; Rhind 1988). Two other events must also be noted about the early development of GIS: publication of Ian McHarg's *Design with Nature* and its inclusion of the map overlay method for suitability analysis (McHarg 1969), and introduction of an urban street network with topology in the U.S. Census Bureau's Dual Independent Map Encoding (DIME) system in the 1970s (Broome and Meixler 1990).

The flourishing of GIS activities in the 1980s was in large part prompted by the introduction of personal computers such as the IBM PC and the graphical user interface such as Microsoft Windows. Unlike mainframes and minicomputers, PCs equipped with graphical user interface were more user friendly, thus broadening the range of GIS applications and bringing GIS to mainstream use in the 1990s. Also in the 1980s, commercial and free GIS packages appeared in the market. Environmental Systems Research Institute, Inc. (Esri) released ARC/INFO, which combined spatial features of points, lines, and polygons with a database management system for linking attributes to these features. Partnered with Intergraph, Bentley Systems developed Microstation, a CAD software product. Other GIS packages developed during the 1980s included GRASS, MapInfo, TransCAD, and Smallworld.

As GIS continually evolves, two trends have emerged in recent years. One, as the core of geospatial technology, GIS has increasingly been integrated with other geospatial data such as satellite images and GPS data. Two, GIS has been linked with Web services, mobile technology, social media, and cloud computing.

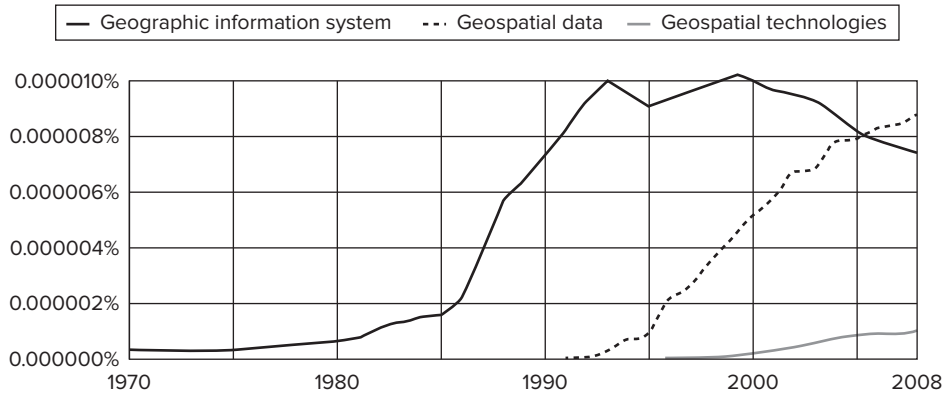


Figure 1.2

Occurrences of the phrases “geographic information system,” “geospatial data,” and “geospatial technologies” in digitized Google books in English from 1970 to 2008 (the last year available). This figure is modified from a Google Books Ngram, accessed in April 2012.

Figure 1.2, an Ngram made in the Google Books Ngram Viewer, shows how the phrases “geographic information system,” “geospatial data,” and “geospatial technologies” occurred in digitized Google books in English from 1970 to 2008. The phrase “geographic information system” rose rapidly from 1980 to the early 1990s, leveled off in the 1990s, and started falling after 2000. In contrast, the other two phrases, especially “geospatial data,” have risen since the 1990s. Figure 1.2 confirms strong integration between GIS and other geospatial data and between GIS and other geospatial technologies.

Along with the proliferation of GIS activities, numerous GIS textbooks have been published. Several journals (*International Journal of Geographical Information Science*, *Transactions in GIS*, and *Cartography and Geographic Information Science*) and a variety of magazines (e.g., *Directions Magazine*, *GIS Geography*, *GISuser*, *GIS Lounge*, *Mondo Geospatial*, *Geospatial World*, and *GeoConnexion*) are now devoted to GIS and GIS applications. Additionally, the importance of geospatial data has been “discovered” in fields such as public health, with publication of journals such as *Geospatial Health*, *Spatial and Spatio-Temporal Epidemiology*, and *International Journal of Health Geographics*. A GIS certification program, sponsored by several

nonprofit associations, is also available to those who want to become certified GIS professionals (<http://www.gisci.org/>). The certification uses a point system that is based on educational achievement, professional experience, and contribution to the profession. There are over 6000 certified GIS professionals, according to a press release from 2016.

1.1.3 GIS Software Products

Box 1.1 shows a select list of commercial GIS software in the left column and free and open source software (FOSS) for GIS in the right column. GIS software companies from the 1980s are still active on the market: Esri with ArcGIS, Intergraph with Geomedia, MapInfo (now Pitney Bowes) with MapInfo, Bentley Systems with Bentley Map, Smallworld Company (now General Electric) with Smallworld, and Caliper with Maptitude (succeeding TransCAD). According to various trade reports, Esri leads the GIS software industry. The main software product from Esri is ArcGIS, which is composed of applications and extensions in a scalable system of three license levels, with the number of tools and functionalities increased at each level (Box 1.2).



Box 1.1 A List of Commercial and Free and Open Source GIS Packages

Commercial

- Environmental Systems Research Institute (Esri) (<http://www.esri.com/>): **ArcGIS**
- Autodesk Inc. (<http://www.autodesk.com/>): **AutoCAD Map3D and Autodesk Geospatial**
- Bentley Systems, Inc. (<http://www.bentley.com/>): **Bentley Map**
- Intergraph/Hexagon Geospatial (<http://www.intergraph.com/>): **GeoMedia**
- Blue Marble (<http://www.bluemarblegeo.com/>): **Global Mapper**
- Manifold (<http://www.manifold.net/>): **Manifold System**
- Pitney Bowes (<http://www.mapinfo.com/>): **MapInfo**
- Caliper Corporation (<http://www.caliper.com/>): **Maptitude**
- General Electric (<https://www.gegridsolutions.com/GIS.htm>): **Smallworld**
- Clark Labs (<http://www.clarklabs.org/>): **TerrSet/IDRISI**

Free and Open Source

- Center for Spatial Data Science, University of Chicago (<http://spatial.uchicago.edu/>): **GeoDa**
- Open Source Geospatial Foundation (<http://grass.osgeo.org/>): **GRASS**
- gvSIG Community (<http://www.gvsig.com/en/>): **gvSIG**
- International Institute for Aerospace Survey and Earth Sciences, the Netherlands (<http://www.itc.nl/ilwis/>): **ILWIS**
- MapWindow GIS Project (<http://mapwindow.org/>): **MapWindow**
- Open Jump (<http://www.openjump.org/>): **OpenJump**
- Quantum GIS Project (<http://www.qgis.org/>): **QGIS**
- SAGA User Group (<http://www.saga-gis.org/>): **SAGA GIS**
- Refractions Research (<http://udig.refractions.net/>): **uDig**



Box 1.2 ArcGIS

ArcGIS is composed of applications and extensions at three license levels. The applications include ArcMap, ArcGIS Pro, ArcCatalog, ArcScene, and ArcGlobe, and the extensions include 3D Analyst, Network Analyst, Spatial Analyst, Geostatistical Analyst, and others. The license levels of Basic, Standard, and Advanced determine the number of tools a user can have for data analysis, data editing, and data management. The core applications for ArcGIS are ArcMap and ArcGIS Pro.

ArcMap was introduced with ArcGIS 8 in 2000 and, over the years, a large number of tools and functionalities have been incorporated into ArcMap. Because of its wide applications, this book uses ArcMap as the main application for chapter exercises. Introduced in 2015, ArcGIS Pro is a new entry in the suite of ArcGIS applications. ArcGIS Pro is a native 64-bit

application, which runs only on a 64-bit operating system. Compared to ArcMap, a 32-bit application which runs on either a 32-bit or a 64-bit operating system, ArcGIS Pro can run faster by processing more data at once. Esri developers have taken advantage of the 64-bit system in the software design of ArcGIS Pro. Special features of ArcGIS Pro include viewing data in 2D and 3D simultaneously, working with multiple maps and layouts, using project-based workflows, and sharing finished maps directly online. These features are ideal for GIS professionals who regularly work with large amounts of data and with other users in the same organization. However, as of early 2017, ArcGISPro does not have all of the functionality found in ArcMap, which perhaps explains why ArcGIS Pro runs side by side with ArcMap.

GRASS GIS (Geographic Resources Analysis Support System), the first FOSS for GIS, was originally developed by the U.S. Army Construction Engineering Research Laboratories in the 1980s. Well known for its analysis tools, GRASS GIS is currently maintained and developed by a worldwide network of users. Trade reports have indicated that QGIS (formerly Quantum GIS) is the most popular FOSS for GIS, with 400 plugins and GRASS GIS as its base analysis tool set. FOSS GIS products have become popular among GIS users in recent years, especially in Europe. A review of FOSS for GIS for building a spatial data infrastructure is available in Steiniger and Hunter (2012).

1.2 ELEMENTS OF GIS

Pedagogically, GIS consists of the following elements: geospatial data, data acquisition, data management, data display, data exploration, and data analysis. Table 1.1 cross-references the elements and the chapters in this book.

1.2.1 Geospatial Data

By definition, geospatial data cover the location of spatial features. To locate spatial features on the Earth's surface, we can use either a geographic or a projected coordinate system. A geographic coordinate system is expressed in longitude and latitude and a projected coordinate system in x, y coordinates. Many projected coordinated systems are available for use in GIS. An example is the Universal Transverse Mercator (UTM) grid system, which divides the Earth's surface between 84°N and 80°S into 60 zones. A basic principle in GIS is that map layers representing different geospatial data must align spatially; in other words, they are based on the same spatial reference.

A GIS represents geospatial data as either vector data or raster data (Figure 1.3). The **vector data model** uses points, lines, and polygons to represent spatial features with a clear spatial location and boundary such as streams, land parcels, and vegetation stands (Figure 1.4). Each feature is assigned an ID so that it can be associated with its attributes.

TABLE 1.1 Elements of GIS and Their Coverage in the Book

Elements	Chapters
Geospatial data	Chapter 2: Coordinate systems Chapter 3: Vector data model Chapter 4: Raster data model
Data acquisition	Chapter 5: GIS data acquisition Chapter 6: Geometric transformation Chapter 7: Spatial data accuracy and quality
Attribute data management	Chapter 8: Attribute data management
Data display	Chapter 9: Data display and cartography
Data exploration	Chapter 10: Data exploration
Data analysis	Chapter 11: Vector data analysis Chapter 12: Raster data analysis Chapter 13: Terrain mapping and analysis Chapter 14: Viewshed and watershed analysis Chapter 15: Spatial interpolation Chapter 16: Geocoding and dynamic segmentation Chapter 17: Least-cost path analysis and network analysis Chapter 18: GIS models and modeling

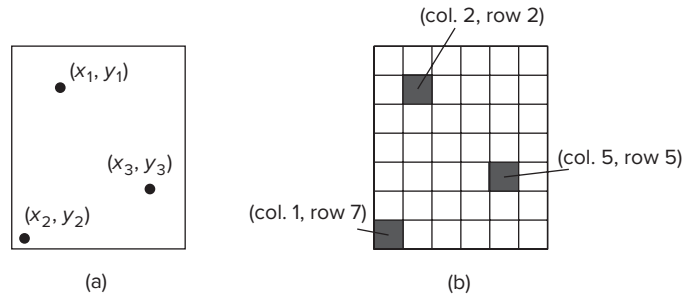


Figure 1.3

The vector data model uses x -, y -coordinates to represent point features (a), and the raster data model uses cells in a grid to represent point features (b).

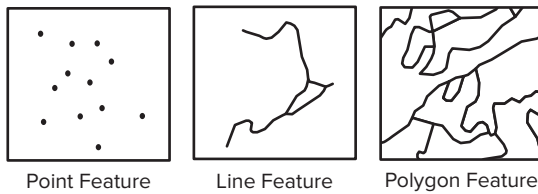


Figure 1.4

Point, line, and polygon features.

The **raster data model** uses a grid and grid cells to represent spatial features: point features are represented by single cells, line features by sequences of neighboring cells, and polygon features by collections of contiguous cells. The cell value corresponds to the attribute of the spatial feature at the cell location. Raster data are ideal for continuous features such as elevation and precipitation (Figure 1.5).

A vector data model can be georelational or object-based, with or without topology, and simple or composite. The **georelational model** stores geometries and attributes of spatial features in separate systems, whereas the **object-based model** stores them in a single system. **Topology** explicitly expresses the spatial relationships between features, such as two lines meeting perfectly at a point. Vector data with topology are necessary for some analyses such as finding shortest paths on a road network, whereas data without topology can display faster. Composite features are built on simple features of points, lines, and polygons; they include the **triangulated irregular network (TIN)** (Figure 1.6),

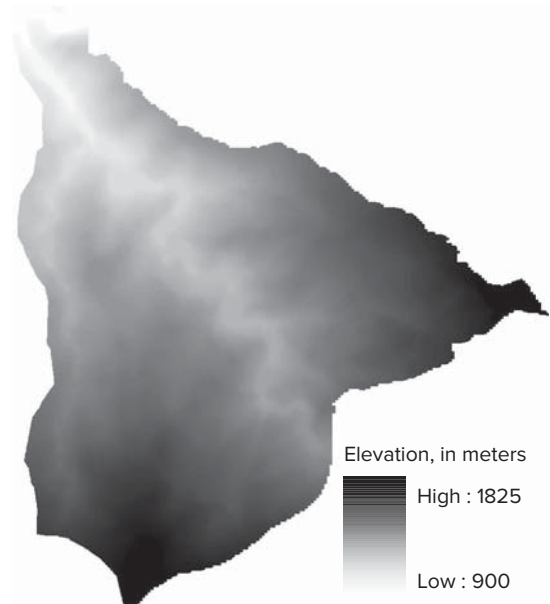


Figure 1.5

A raster-based elevation layer.

which approximates the terrain with a set of non-overlapping triangles, and **dynamic segmentation** (Figure 1.7), which combines one-dimensional linear measures such as mileposts with two-dimensional projected coordinates.

A large variety of data used in GIS are encoded in raster format such as digital elevation models and satellite images. Although the raster representation of spatial features is not precise, it has the distinctive

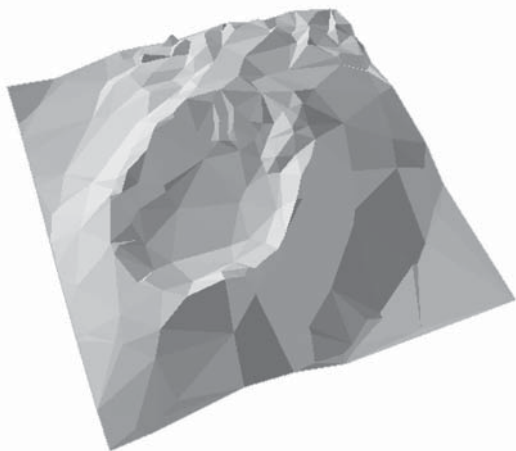


Figure 1.6
An example of the TIN model.

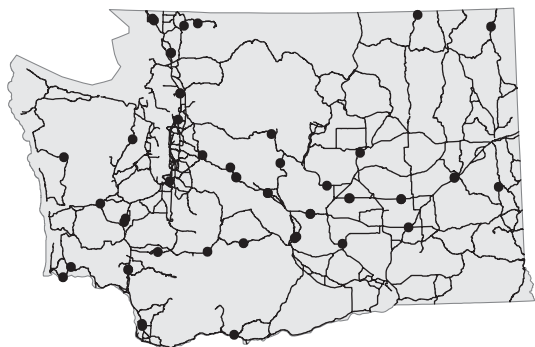


Figure 1.7
Dynamic segmentation allows rest areas, which are linearly referenced, to be plotted as point features on highway routes in Washington State.

advantage of having fixed cell locations, thus allowing for efficient manipulation and analysis in computing algorithms. Raster data, especially those with high spatial resolutions, require large amounts of computer memory. Therefore, issues of data storage and retrieval are important to GIS users.

1.2.2 Data Acquisition

Data acquisition is usually the first step in conducting a GIS project. The need for geospatial data by GIS users has been linked to the development of

data clearinghouses and geoportals. Since the early 1990s, government agencies at different levels in the United States as well as many other countries have set up websites for sharing public data and for directing users to various data sources. To use public data, it is important to obtain metadata, which provide information about the data. If public data are not available, new data can be digitized from paper maps or orthophotos, created from satellite images, or converted from GPS data, survey data, street addresses, and text files with x - and y -coordinates. Data acquisition therefore involves compilation of existing and new data. To be used in a GIS, a newly digitized map or a map created from satellite images requires geometric transformation (i.e., georeferencing). Additionally, both existing and new spatial data must be edited if they contain digitizing and/or topological errors.

1.2.3 Attribute Data Management

A GIS usually employs a database management system (DBMS) to handle attribute data, which can be large in size in the case of vector data. Each polygon in a soil map, for example, can be associated with dozens of attributes on the physical and chemical soil properties and soil interpretations. Attribute data are stored in a **relational database** as a collection of tables. These tables can be prepared, maintained, and edited separately, but they can also be linked for data search and retrieval. A DBMS offers join and relate operations. A join operation brings together two tables by using a common attribute field (e.g., feature ID), whereas a relate operation connects two tables but keeps the tables physically separate. Spatial join is unique in GIS as it uses spatial relationships to join two sets of spatial features and their attribute data, such as joining a school to a county in which the school is located. A DBMS also offers tools for adding, deleting, and manipulating attributes.

1.2.4 Data Display

A routine GIS operation is mapmaking because maps are an interface to GIS. Mapmaking can be informal or formal in GIS. It is informal when we view geospatial data on maps, and formal when we

produce maps for professional presentations and reports. A professional map combines the title, map body, legend, scale bar, and other elements together to convey geographic information to the map reader. To make a “good” map, we must have a basic understanding of map symbols, colors, and typology, and their relationship to the mapped data. Additionally, we must be familiar with map design principles such as layout and visual hierarchy. After a map is composed in a GIS, it can be printed or saved as a graphic file for presentation. It can also be converted to a KML file, imported into Google Earth, and shared publicly on a web server. For time-dependent data such as population changes over decades, a series of map frames can be prepared and displayed in temporal animation.

1.2.5 Data Exploration

Data exploration refers to the activities of visualizing, manipulating, and querying data using maps, tables, and graphs. These activities offer a close look at the data and function as a precursor to formal data analysis. Data exploration in GIS can be map- or feature-based. Map-based exploration includes data classification, data aggregation, and map comparison. Feature-based query can involve either attribute or spatial data. Attribute data query is basically the same as database query using a DBMS. In contrast, spatial data query allows GIS users to select features based on their spatial relationships such as containment, intersect, and proximity. A combination of attribute and spatial data queries provides a powerful tool for data exploration.

1.2.6 Data Analysis

A GIS has a large number of tools for data analysis. Some are basic tools, meaning that they are regularly used by GIS users. Other tools tend to be discipline or application specific. Two basic tools for vector data are buffering and overlay: buffering creates buffer zones from select features, and overlay combines the geometries and attributes of the input layers (Figure 1.8). Four basic tools for raster data are local (Figure 1.9), neighborhood, zonal,

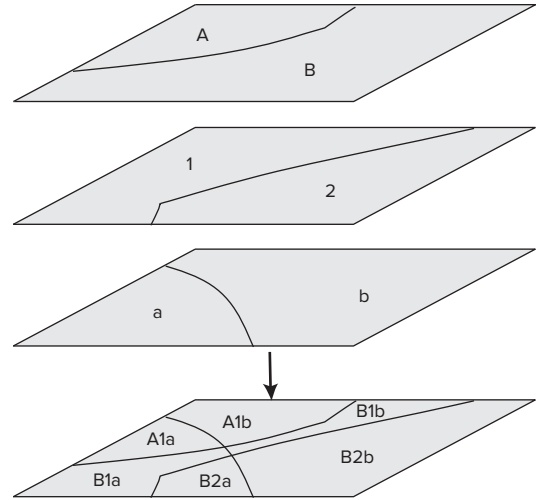


Figure 1.8

A vector-based overlay operation combines geometries and attributes from different layers to create the output.

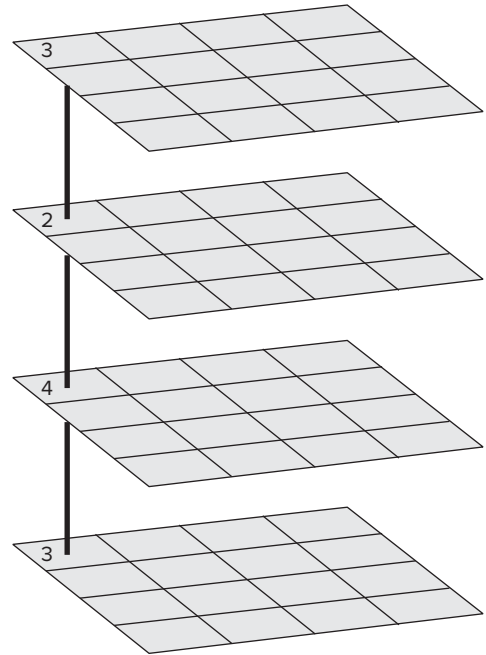


Figure 1.9

A raster data operation with multiple rasters can take advantage of the fixed cell locations. For example, a local average can easily be computed by dividing the sum of 3, 2, and 4 (9) by 3.