Ninth Edition

Introduction to

GEOGRAPHIC INFORMATION SYSTEMS

KANG-TSUNG CHANG

McGraw Hill Education

Ninth Edition

Introduction to Geographic Information Systems

Kang-tsung Chang
University of Idaho

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INTRODUCTION TO GEOGRAPHIC INFORMATION SYSTEMS, NINTH EDITION

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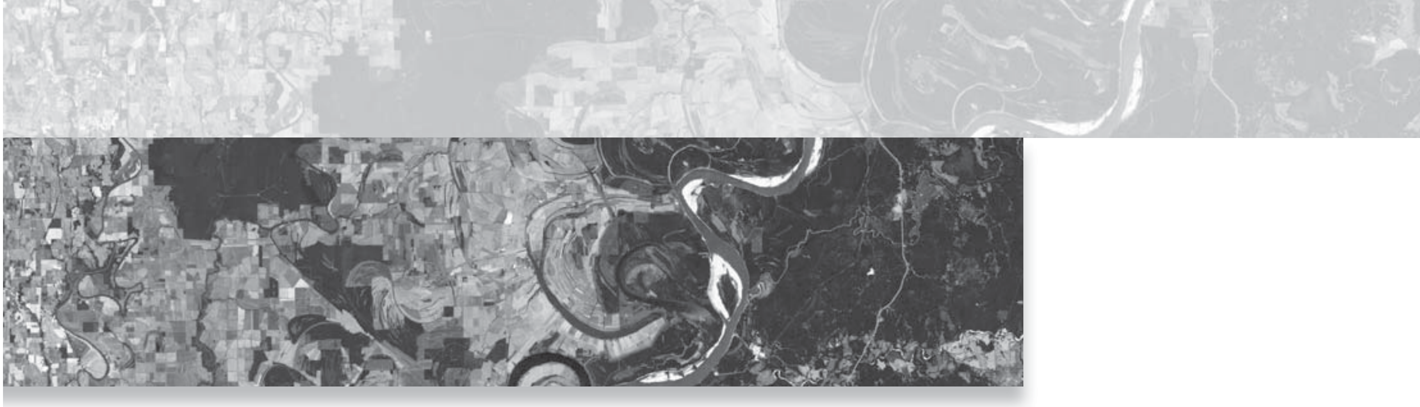

Brief Contents

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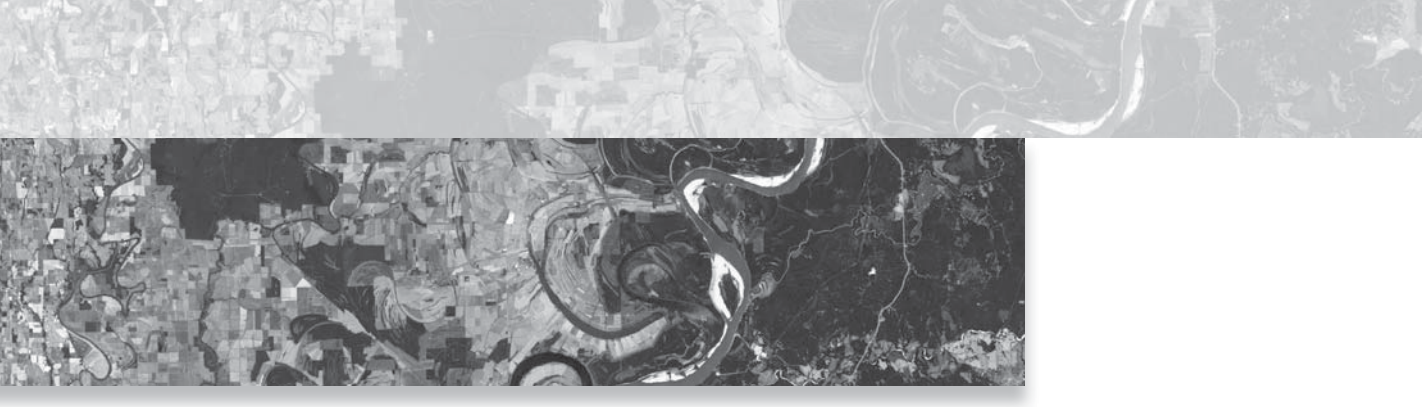

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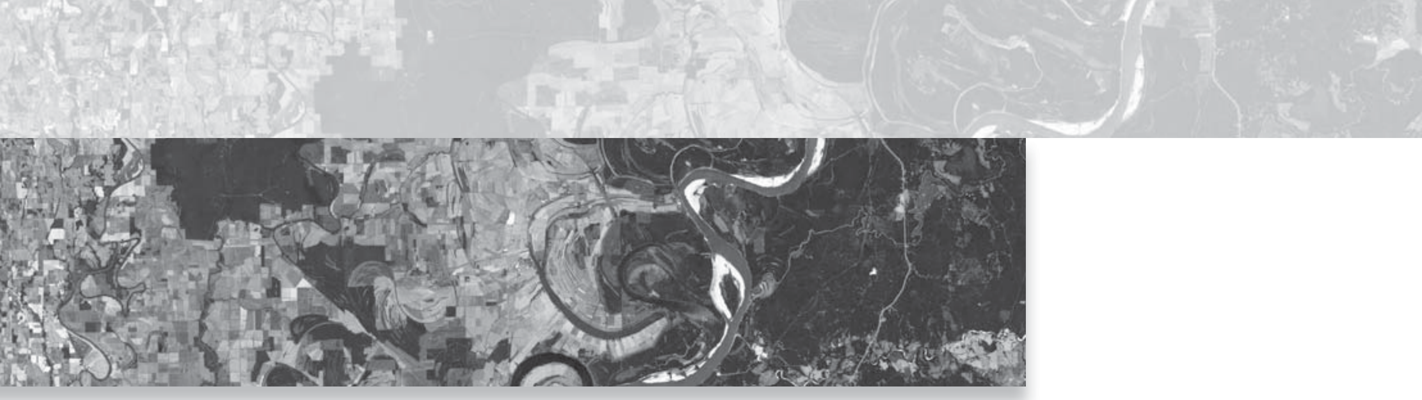

Preface

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

Wyoming Geospatial Hub
http://geospatialhub.org/

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Kang-tsung Chang

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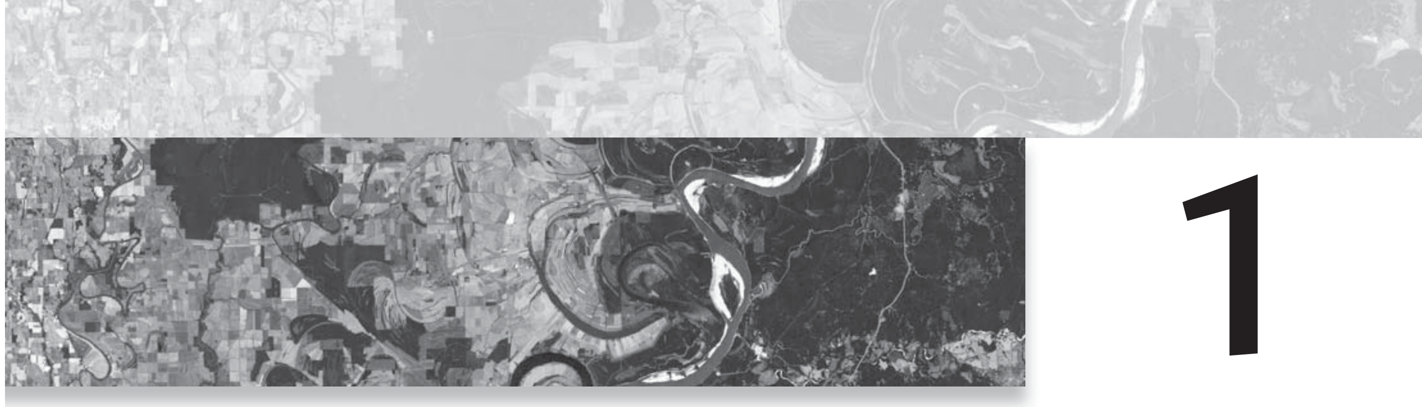

1

Introduction

Chapter Outline

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

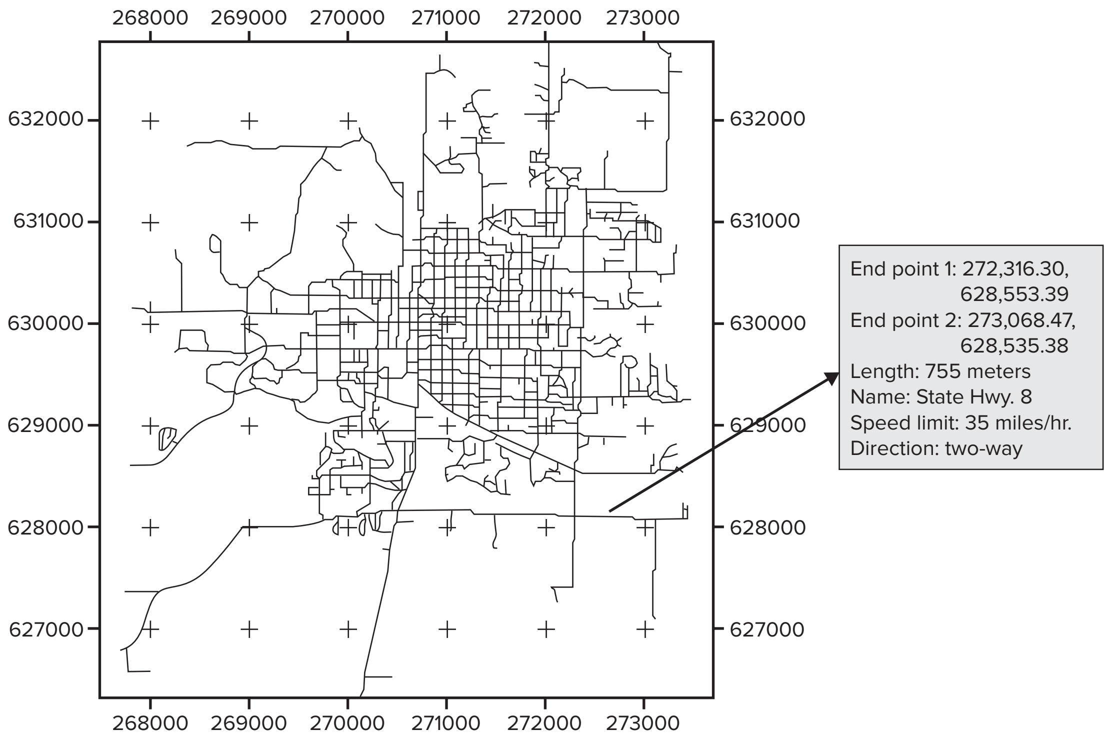

Figure 1.1
An example of geospatial data. The street network is based on a plane coordinate system. The box on the right lists the *x*- and *y*-coordinates of the end points and other attributes of a street segment.

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.

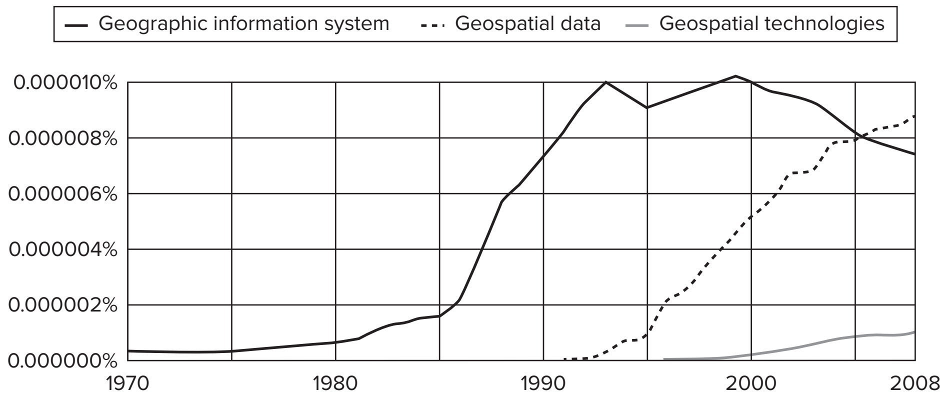

Figure 1.2
Occurrences of the phrases "geographic information system," "geospatial data," and "geospatial technologies" in digitized Google books in English from 1970 to 2008 (the last year available). This figure is modified from a Google Books Ngram, accessed in April 2012.

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 *GeoConnextion*) 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

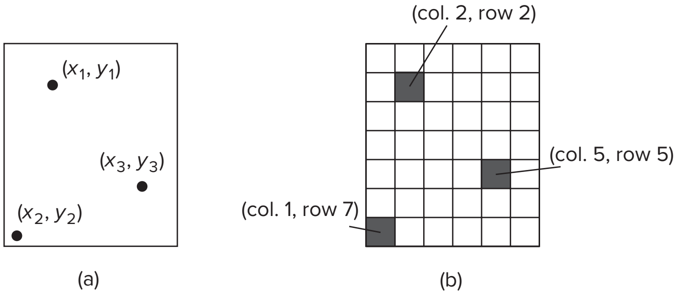

Figure 1.3
The vector data model uses *x*-, *y*-coordinates to represent point features (*a*), and the raster data model uses cells in a grid to represent point features (*b*).

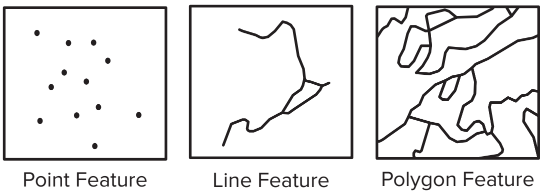

Figure 1.4
Point, line, and polygon features.

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).

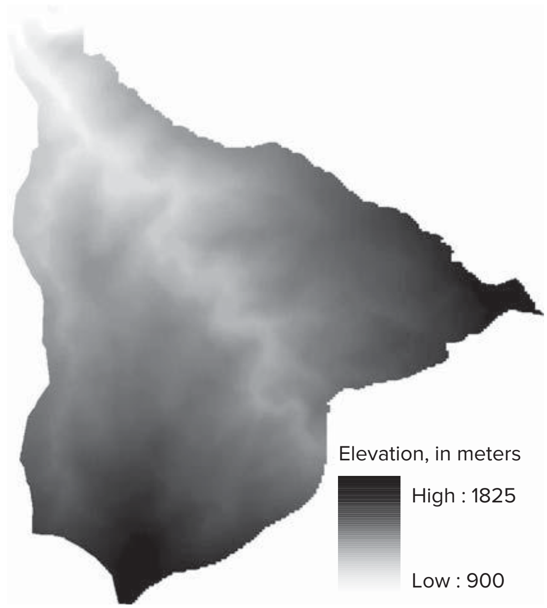

Figure 1.5
A raster-based elevation layer.

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), 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

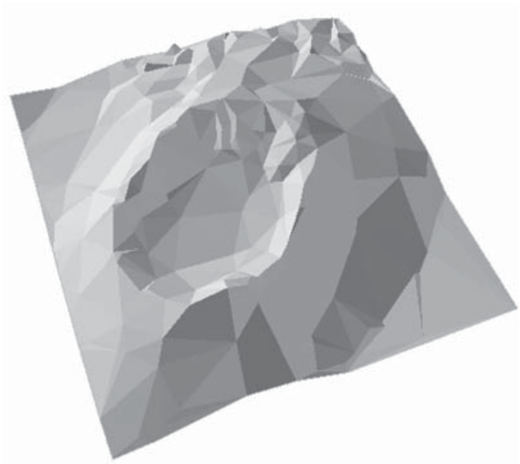

Figure 1.6
An example of the TIN model.

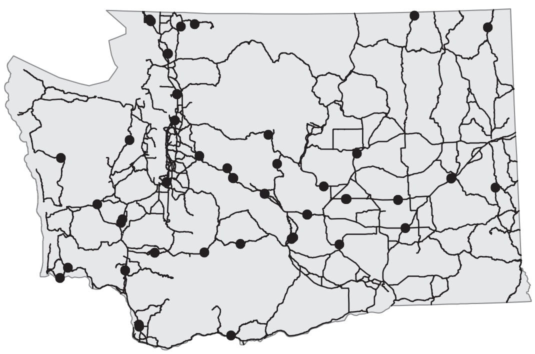

Figure 1.7
Dynamic segmentation allows rest areas, which are linearly referenced, to be plotted as point features on highway routes in Washington State.

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.

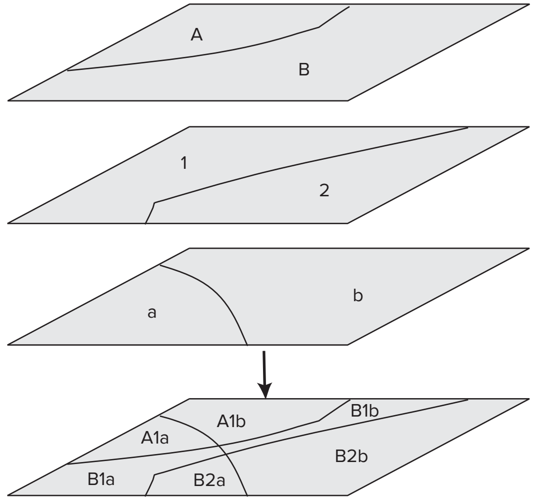

Figure 1.8
A vector-based overlay operation combines geometries and attributes from different layers to create the output.

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,

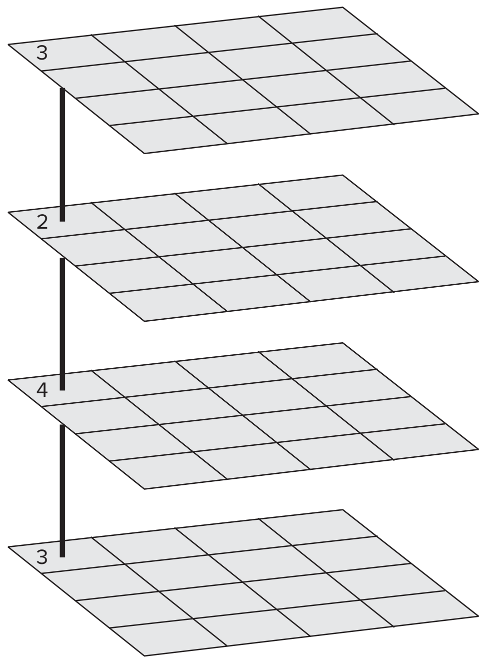

Figure 1.9
A raster data operation with multiple rasters can take advantage of the fixed cell locations. For example, a local average can easily be computed by dividing the sum of 3, 2, and 4 (9) by 3.

and global operations, depending on whether the operation is performed at the level of individual cells, or groups of cells, or cells within an entire raster.

The terrain is important for studies of timber management, soil erosion, hydrologic modeling, and wildlife habitat suitability. A GIS has tools for mapping the terrain in contours, profiles, hill shading, and 3-D views, and for analyzing the terrain with slope, aspect, and surface curvature. Terrain analysis also includes viewshed and watershed: a viewshed analysis determines areas visible from one or more observation points, and a watershed analysis traces water flow to delineate stream networks and watersheds.

Spatial interpolation uses points with known values to estimate values at other points. When applied in GIS, spatial interpolation is a means of creating surface data from sample points. A variety of methods are available for spatial interpolation ranging from global to local and from deterministic to stochastic. Among them, kriging is a method that can not only predict unknown values but also estimate prediction errors.

Geocoding converts postal addresses into point features, and dynamic segmentation locates linearly referenced data on an *x*-, *y*-coordinate system. They can be considered as tools for creating new GIS data by using linear features (e.g., streets, highways) as references. Therefore, for some GIS users, they can be treated as topics in data acquisition. Geocoding is important for location-based services, crime analysis, and other applications, and dynamic segmentation is primarily designed for the display, query, and analysis of transportation-related data.

Least-cost path analysis finds the least accumulated cost path in a raster, and network analysis solves for the shortest path between stops on a topological road network. The two analyses share common concepts in GIS but differ in applications. Least-cost path analysis is raster-based and works with "virtual" paths, whereas network analysis is vector-based and works with an existing road network.

A GIS and its tools can be used to build spatially explicit models that separate areas that satisfy a set of selection criteria from those that do not, or rank areas based on multicriteria evaluation. A GIS can also help build regression models and process models and assist modelers in data visualization, database management, and data exploration.

1.3 Applications of GIS

GIS is a useful tool because a high percentage of information we routinely encounter has a spatial component. An often cited figure among GIS users is that 80 percent of data is geographic. To validate the 80 percent assertion, Hahmann and Burghardt (2013) use the German Wikipedia as the data source and report that 57 percent of information is geospatially referenced. Although their finding is lower than 80 percent, it is still strong evidence for the importance of geospatial information and, by extension, GIS and GIS applications.

Since its beginning, GIS has been important for land use planning, natural hazard assessment, wildlife habitat analysis, riparian zone monitoring, timber management, and urban planning. The list of fields that have benefited from the use of GIS has expanded significantly for the past three decades. Box 1.3 lists results of a keyword search of fields, which are linked to GIS applications.

In the United States, the U.S. Geological Survey (USGS) is a leading agency in the development and promotion of GIS. The USGS website provides case studies as well as geospatial data for applications in climate and land use change, ecosystem analysis, geologic mapping, petroleum resource assessment, watershed management, coastal zone management, natural hazards (volcano, flood, and landslide), aquifer depletion, and ground water management **(http://www.usgs.gov/).** With a focus on census data and GIS applications, the U.S. Census Bureau provides GIS-compatible TIGER (Topologically Integrated Geographic Encoding and Referencing) products, including legal and statistical geographic areas, roads, railroads, and rivers, which can be combined with demographic and economic data for a wide variety of analyses **(http://www.census.gov/).**

Box 1.3 A List of GIS Applications

A quick keyword search of GIS applications in Google Scholar results in the following fields: natural resources, natural hazards, surface and groundwater hydrology, meteorology, environmental analysis and monitoring, flood risk, soils, ecosystem management, wildlife habitat, agriculture, forestry, landscape analysis and management, land use management, invasive species, estuarine management, archaeology, urban planning, transportation, health care, business and service planning, real estate, tourism, community planning, emergency response planning, pollution assessment, public services, and military operations.

Many of these fields such as natural resources, agriculture, and forestry are quite general and can have many subfields. Therefore, this list of GIS applications is not complete and will continue to expand in the future.

A number of other U.S. federal agencies also offer GIS data and applications on their website:

- The U.S. Department of Housing and Urban Development's GIS portal offers tools for locating Empowerment Zones, Renewal Communities, Enterprise Communities, and HUD homes available for sale. It also has tools for preparing and mapping communities and neighborhoods for HUD's grant programs **(https://www.huduser.gov/portal/egis/index.html).**
- The U.S. Department of Health and Human Services' data warehouse provides access to information about health resources including community health centers **(http://datawarehouse.hrsa.gov/).**
- The National Weather Service's GIS portal delivers GIS-compatible weather data such as precipitation estimates, hydro-meteorological data, and radar imagery **(http://www.weather.gov/gis/).** Current and historical data on tropical cyclone wind speeds and tracks are available through its Hurricane Center **(http://www.nhc.noaa.gov/).**
- The Federal Highway Administration's GIS in transportation website has a link to GIS applications, including state and local GIS practices, FHWA GIS efforts, and national applications **(http://www.gis.fhwa.dot.gov/apps.asp).**
- The Forest Service's Geospatial Service and Technology Center delivers a range of geographic information products and related technical and training services **(http://www.fs.fed.us/gstc/).**
- The U.S. Department of Agriculture's program on precision, geospatial, and sensor technologies focuses on site-specific crop management and other topics **(https://nifa.usda.gov/program/precision-geospatial-sensor-technologies-programs)** (Box 1.4).

In the private sector, most GIS applications are integrated with the Internet, GPS, wireless technology, and Web services. The following shows some of these applications:

- Online mapping websites offer locators for finding real estate listings, vacation rentals, banks, restaurants, coffee shops, and hotels.
- Location-based services allow mobile phone users to search for nearby banks, restaurants, and taxis; and to track friends, dates, children, and the elderly (Box 1.5).
- Mobile GIS allows field workers to collect and access geospatial data in the field.

Box 1.4 Precision Farming

Site-specific crop management is synonymous with precision farming, one of the earlier GIS applications. Farmers started to use precision farming in the late 1980s for applying fertilizers to their field according to different soil conditions. Gebbers and Adamchuk (2010) report that modern precision farming can achieve the following three goals: (1) optimize the use of available resources to increase the profitability and sustainability of agricultural operations, (2) reduce negative environmental impact, and (3) improve the quality of the work environment and the social aspects of farming, ranching, and relevant professions. According to them, precision farming is crucial to food security for the future.

Box 1.5 Location-Based Services and Social Networking

The third edition (2005) of this book introduced the location-based service of Dodgeball as an example of bridging GIS and social networking. Dodgeball's tagline was "locate friends and friends-of-friends within 10 blocks." It was a huge success, leading to Google buying Dodgeball in 2005. But the partnership did not work out and in 2009 one of the founders of Dodgeball set up Foursquare, a location-based social networking website for mobile devices. Users of Foursquare applications can post their location at a venue in Twitter or Facebook and connect with their friends. Of course, Foursquare is not the only location-based social networking website; Facebook Places, Glympse, Google Now, and Waze provide similar services.

- Mobile resource management tools track and manage the location of field crews and mobile assets in real time.
- Automotive navigation systems provide turn-by-turn guidance and optimal routes based on precise road mapping using GPS and camera.
- Market area analysis identifies areas worthy of expansion by examining branch locations, competitor locations, and demographic characteristics.
- Augmented reality lets a smartphone user look through the phone's camera with superimposed data or images (e.g., 3-D terrain from a GIS, monsters in Pokémon Go) about the current location.

1.4 Integration of GIS, Web2.0, and Mobile Technology

This section examines new and important developments in combining GIS, Web 2.0, and mobile technology. They are not "traditional" GIS applications in the sense of how we use desktop GIS to perform routine tasks in projection, data management, data exploration, and data analysis; instead, they follow the idea of Web 2.0 by focusing on applications that facilitate user-centered design and collaboration. These popular applications have actually brought GIS to the general public and broadened the use of GIS in our daily life.

1.4.1 Web Mapping

For **Web mapping,** the server provides maps and images through a browser (e.g., a map-based browser), which are accessed by the client for data display, data query, and mapping. In 1996, MapQuest offered the first online mapping services, including address matching and travel planning with the map output. Other mapping services were quickly set up by the USGS in 1997 and the U.S. Census Bureau in 2001. Then in 2004, NOAA introduced World Wind, a free, open-source program that allows users to overlay satellite imagery, aerial photographs, topographic maps, and GIS data on 3-D models of the Earth.

Although Web mapping had become common by the early 2000s, it was not until 2005, when Google introduced Google Maps and Google Earth, that Web mapping became popular with the general public. Google Maps lets users search for an address or a business and get travel directions to the location. Google Earth displays the 3-D maps of the Earth's surface, as the user zooms in from space down to street level (Butler 2006). Google has continued to add new features, such as street views, 3D buildings, and Google Trips, to Google Maps and Google Earth since 2005. Google has also purchased Skybox Imaging (renamed Terra Bella in 2016) to have its own up-to-date imagery. The success of Google Maps has led to comparable services from other companies including Bing Maps (formerly Microsoft Virtual Earth), Yahoo! Maps, Apple Maps, and HERE (co-owned by Audi, BMW, and Daimler).

The popularity of Web mapping has broken down the barriers to the public use of geospatial data and technologies, which in turn has led to other developments such as mashup mapping, collaborative Web mapping, volunteered geographic information, and geosocial data exploration, as briefly described in the following subsections.

1.4.2 Mashup Mapping

Mashup mapping allows users to become "instant new cartographers" by combining their contents (e.g., text, photos, and videos) with Web-based maps (Liu and Palen 2010). In 2006, Google Maps introduced a free Application Programming Interface (API) to make "Google Maps mashups." Examples of Google Maps mashups can be viewed at Google Maps Mania **(http://www.googlemapsmania.blogspot.com/)** and Wikimapia **(http://wikimapia.org).** The idea of Google Maps mashups has quickly found its commercial applications in real estate, vacation rentals, quasi-taxi service, and many others. An add-on to Google Maps, My Maps, was introduced in 2007, allowing users to mark locations, paths, and regions of interest on a personalized map, and to embed the map on a website or blog.

Mashup mapping is also available on websites maintained by government agencies. For example, the Geospatial Platform **(http://www.geoplatform.gov/),** introduced by the Federal Geographic Data Committee in 2011, lets users create maps by combining their own data with existing public-domain data. These maps created on the Geospatial Platform can then be shared with other people through browsers and mobile technologies.

For GIS users, mashup mapping can take a different form by integrating layers and maps generated from a GIS package with Google Earth. This is done by converting layers and maps into KML (Keyhole Markup Language) format, the file format used by Google Earth to display geographic data. KML files are also available for download from some government agencies: nation- and state-based boundaries from the U.S. Census Bureau; stream flows, stream gages, and basin boundaries from the USGS; and hydro-meteorological data from the National Weather Service.

1.4.3 Collaborative Web Mapping

As mashup mapping becomes easily available to the general public, it is natural for users to collaborate on projects. One of the most utilized and cited projects is OpenStreetMap (OSM), launched in 2004 (Neis and Zielstra 2014). Often described as the Free Wiki World Map providing free geographic data to anyone, OSM is a collaborative project among registered users who voluntarily collect data, such as road networks, buildings, land use, and public transportation, using GPS, aerial photographs, and other free sources **(https://www.openstreetmap.org/).** The OSM community has been active in disaster relief projects, including the post-earthquake mapping effort in Haiti (Meier 2012). As of 2016, OSM claims to have 3 million users around the globe.

Another example of collaborative Web mapping is Flightradar24, which shows real-time aircraft flight information on a map **(https://www.flightradar24.com/).** Launched in 2006, Flightradar24 aggregates data from multiple sources, including information gathered by volunteers with ADS-B (Automatic dependent surveillance-broadcast) receivers. There are many other collaborative Web mapping projects initiated by communities and organizations. Some have actually used OSM technology in their work, as shown in the community mapping of neighborhood food resources in Philadelphia (Quinn and Yapa 2016).

1.4.4 Volunteered geographic information

Volunteered geographic information (VGI) is a term coined by Goodchild (2007) to describe geographic information generated by the public using Web applications and services. VGI is another example of public-generated or crowdsourced geographic information. In many cases, VGI cannot be separated from collaborative Web mapping. For example, OSM relies on VGI to put together road or bicycle route maps. However, because it can provide near real-time data, VGI is especially useful for disaster management (Haworth and Bruce 2015). The real-time data, combining geotagged images and social media contents, can enable the rapid sharing of important information for disaster management. VGI has been reported to be useful in managing forest fires in southern California (Goodchild and Glennon 2010), and the earthquake in Haiti (Zook et al. 2010). VGI is also used in the private sector. For example, Map Creator **(https://mapcreator.here.com)** lets HERE users report changes to address locations, shops, roads, bridges, and other features common in HERE maps.

A major concern with VGI is its accuracy and reliability, regarding the geographic location and the narratives (e.g., Haklay et al. 2010). Another concern is its ethical use; the kinds of personal information shared during a disaster event may present potential risks as they can be accessed by many people, including those with unethical intentions (Crawford and Finn 2015).

1.4.5 Geosocial Data Exploration

Geosocial data refer to geotagged posts on social networks such as Facebook, Twitter, Instagram, Flickr, and YouTube. By using a smartphone or other types of GPS-enabled devices, people can easily collect and share their location data as well as up-to-date information associated with the locations. Geosocial data can be used for disaster management, as described in Section 1.4.4, but they can have a wider range of applications, including systems recommendations, traffic monitoring, urban planning, public health, and celebrity tracking (Kanza and Samet 2015).

Coded with location and time for each user, geosocial data can often be massive and present a new challenge in GIS (Sui and Goodchild 2011). Studies by Crampton et al. (2013) and Shelton et al. (2014) have advocated that, in working with "big data," we should go beyond the static visualization of geotagged data and pay attention to social and spatial processes behind the data.

1.5 Organization of This Book

Based on the elements of GIS outlined in Section 1.2, this book is organized into six main parts: geospatial data (Chapters 2–4), data acquisition (Chapters 5–7), attribute data management (Chapter 8), data display (Chapter 9), data exploration (Chapter 10), and data analysis (Chapters 11–18) (Table 1.1). The eight chapters on data analysis include: core data analysis in Chapters 11 and 12; terrain analysis in Chapters 13 and 14; spatial interpolation in Chapter 15; geocoding and dynamic segmentation in Chapter 16;

path and network analysis in Chapter 17; and GIS models and modeling in Chapter 18. This book does not have a chapter dedicated to remote sensing or Web applications; instead, these topics are incorporated into various chapters and end-of-chapter tasks.

1.6 CONCEPTS AND PRACTICE

Each chapter in this book has two main sections. The first section covers a set of topics and concepts, and the second section covers applications with two to seven problem-solving tasks. Additional materials in the first section include information boxes, websites, key concepts and terms, and review questions. The applications section provides step-by-step instructions as well as questions to reinforce the learning process. We do not learn well by merely following the instructions to complete a task without pausing and thinking about the process. A challenge question is also included at the end of each applications section to further develop the necessary skills for problem solving. Each chapter concludes with an extensive, updated bibliography.

This book stresses both concept and practice. GIS concepts explain the purpose and objectives of GIS operations and the interrelationship among GIS operations. A basic understanding of map projection, for example, explains why map layers are often projected into a common coordinate system for spatial alignment and why numerous projection parameters are required as inputs. Knowledge of map projection is long lasting, because the knowledge will neither change with the technology nor become outdated with new versions of a GIS package.

GIS is a science as well as a problem-solving tool (Wright, Goodchild, and Proctor 1997; Goodchild 2003). To apply the tool correctly and efficiently, one must become proficient in using the tool. Practice, which is a regular feature in mathematics and statistics textbooks, is really the only way to become proficient in using GIS. Practice can also help one grasp GIS concepts. For instance, the root mean square (RMS) error, an error measure for geometric transformation, may be difficult to comprehend mathematically; but after a couple of geometric transformations, the RMS error starts to make more sense because the user can see how the error measure changes each time with a different set of control points.

Practice sections in a GIS textbook require data sets and GIS software. Many data sets used in this book are from GIS classes taught at the University of Idaho and National Taiwan University over a period of more than 20 years, while some are downloaded from the Internet. Instructions accompanying the exercises correlate to ArcGIS 10.5. Most tasks use ArcGIS with a license level of Basic and the extensions of Spatial Analyst, 3D Analyst, Geostatistical Analyst, Network Analyst, and ArcScan.

Whenever possible, this book provides URLs so that the reader can use them to gather additional information or data. Some of these URLs, however, may become broken after this book is published. In many cases, you can find the new URLs through keyword search.

KEY CONCEPTS AND TERMS

Data exploration: Data-centered query and analysis.

Dynamic segmentation: A data model that allows the use of linearly measured data on a coordinate system.

Geographic information system (GIS): A computer system for capturing, storing, querying, analyzing, and displaying geospatial data.

Georelational data model: A vector data model that uses a split system to store geometries and attributes.

Geosocial data: Geotagged posts on social networks such as Twitter and Instagram.

Geospatial data: Data that describe both the locations and characteristics of spatial features on the Earth's surface.

Mashup Mapping: Mapping that combines the user's contents (e.g., text, photos, and videos) with Web-based maps.

Object-based data model: A data model that uses objects to organize spatial data and stores geometries and attributes in a single system.

Raster data model: A data model that uses a grid and cells to represent the spatial variation of a feature.

Relational database: A collection of tables that are connected to one another by keys.

Topology: A subfield of mathematics that, when applied to GIS, ensures that the spatial relationships between features are expressed explicitly.

Triangulated irregular network (TIN): Composite vector data that approximate the terrain with a set of nonoverlapping triangles.

Vector data model: A spatial data model that uses points and their *x*-, *y*-coordinates to construct spatial features of points, lines, and polygons.

Volunteered geographic information: Geographic information generated by the public using Web applications and services.

REVIEW QUESTIONS

1. Define geospatial data.
2. Describe an example of GIS application from your discipline.
3. Go to the USGS National Map website (**http://nationalmap.gov/viewer.html**) and see what kinds of geospatial data are available for download.
4. Go to the National Institute of Justice website **(http://www.ojp.usdoj.gov/nij/maps/)** and read how GIS is used for crime analysis.
5. Location-based services are probably the most commercialized GIS-related field. Search for "location-based service" on Wikipedia **(http://www.wikipedia.org/)** and read what has been posted on the topic.
6. What types of software and hardware are you currently using for GIS classes and projects?
7. Try the map locators offered by Microsoft Virtual Earth, Yahoo! Maps, and Google Maps, respectively. State the major differences among these three systems.
8. Define geometries and attributes as the two components of GIS data.
9. Explain the difference between vector data and raster data.
10. Explain the difference between the georelational data model and the object-based data model.
11. Provide an example of mashup mapping.
12. Why is "volunteered geographic information" useful for disaster management?
13. The following link, **http://www.openstreetmap.org/#map=12/52.1977/0.1507,** shows a map of Cambridge, England, based on OpenStreetMap data. Use the map to compare the quality of OpenStreetMap data with Google Maps.
14. Suppose you are required to do a GIS project for a class. What types of activities or operations do you have to perform to complete the project?
15. Name *two* examples of vector data analysis.
16. Name *two* examples of raster data analysis.
17. Describe an example from your discipline in which a GIS can provide useful tools for building a model.

APPLICATIONS: INTRODUCTION

ArcGIS uses a single scalable architecture and user interface. It has three license levels: Basic, Standard, and Advanced. All three levels use the same applications of ArcCatalog and ArcMap and share the same extensions such as Spatial Analyst, 3D Analyst, Network Analyst, and Geostatistical Analyst. They, however, have different sets of operations they can perform. This book uses ArcGIS 10.5.

Both ArcCatalog and ArcMap have the Customize menu. When you click on Extensions on the Customize menu, it displays a list of extensions and allows you to select the extensions to use. If the controls of an extension (e.g., Geostatistical Analyst) are on a toolbar, you must also check its toolbar (e.g., Geostatistical Analyst) from the Toolbars pullright in the Customize menu.

This applications section covers two tasks. Task 1 introduces ArcCatalog and ArcToolbox, and Task 2 ArcMap and the Spatial Analyst extension. Vector and raster data formats used in the two tasks are covered in Chapters 3 and 4, respectively. Typographic conventions used in the instructions include italic typeface for data sets (e.g., *emidalat*) and boldface for questions (e.g., **Q1**).

Task 1 Introduction to ArcCatalog

What you need: *emidalat*, an elevation raster; and *emidastrm.shp*, a stream shapefile.

Task 1 introduces ArcCatalog, an application for managing data sets.

1. Start ArcCatalog in the program menu. ArcCatalog lets you set up connections to your data sources, which may reside in a folder on a local disk or on a database on the network. For Task 1, you will first connect to the folder containing the Chapter 1 database (e.g., chap1). Click the Connect to Folder button. Navigate to the chap1 folder and click OK. The chap1 folder now appears in the Catalog tree under Folder Connections. Expand the folder to view the data sets.
2. Click *emidalat* in the Catalog tree. Click the Preview tab to view the elevation raster. Click *emidastrm.shp* in the Catalog tree. On the Preview tab, you can preview the geography or table of *emidastrm.shp*.
3. ArcCatalog has tools for various data management tasks. You can access these tools by right-clicking a data set to open its context menu. Right-click *emidastrm.shp*, and the menu shows Copy, Delete, Rename, Create Layer, Export, and Properties. Using the context menu, you can copy *emidastrm.shp* and paste it to a different folder, rename it, or delete it. A layer file is a visual representation of a data set. The export tool can export a shapefile to a geodatabase and other formats. The properties dialog shows the data set information. Right-click *emidalat* and select Properties. The Raster Dataset Properties dialog shows that *emidalat* is a raster dataset projected onto the Universal Transverse Mercator (UTM) coordinate system.
4. This step lets you create a personal geodatabase and then import *emidalat* and *emidastrm.shp* to the geodatabase. Right-click the Chapter 1 database in the Catalog tree, point to New, and select Personal Geodatabase (you can do the same using the File menu). Click the new geodatabase and rename it *Task1.mdb*. If the extension .mdb does not appear, select ArcCatalog Options from the Customize menu and on the General tab, uncheck the box to hide file extensions.
5. There are two options for importing *emidalat* and *emidastrm.shp* to *Task1.mdb*. Here you use the first option to import *emidalat*. Right-click *Task1.mdb*, point to Import, and select Raster Datasets. In the next dialog, navigate to *emidalat*, add it for the input raster, and click OK to import. You will get a message on

the screen when the import operation is completed. (You will also see a message with a red X if the operation fails.)

6. Now you will use the second option, ArcToolbox, to import *emidastrm.shp* to *Task1.mdb*. ArcCatalog's standard toolbar has a button called ArcToolbox. Click the button to open ArcToolbox. Right-click ArcToolbox, and select Environments. The Environment Settings dialog can let you set the workspace, which is important for most operations. Click the dropdown arrow for Workspace. Navigate to the Chapter 1 database and set it to be the current workspace and the scratch workspace. Close the Environment Settings window. Tools in ArcToolbox are organized into a hierarchy. The tool you need for importing *emidastrm.shp* resides in the Conversion Tools/To Geodatabase toolset. Double-click Feature Class to Feature Class to open the tool. Select *emidastrm.shp* for the input features, select *Task1.mdb* for the output location, specify *emidastrm* for the output feature class name, and click OK. Expand *Task1.mdb* and make sure that the import operations have been completed.

Q1. The number of usable tools in ArcToolbox varies depending on which license of ArcGIS you are using. The licensing information is available in ArcGIS 10.5 Desktop Help in the program menu, arranged by the toolbox. For example, to get the licensing information for the Feature Class to Feature Class tool, you will go to Tool reference/Conversion toolbox/Conversion toolbox licensing. Is the Feature Class to Feature Class tool for Task 1 available to all three license levels of ArcGIS?

Task 2 Introduction to ArcMap

What you need: *emidalat* and *emidastrm.shp*, same as Task 1.

In Task 2, you will learn the basics of working with ArcMap. Starting in ArcGIS 10.0, ArcMap has the Catalog button that lets you open Catalog directly in ArcMap. Catalog allows you to perform the same functions and tasks such as copy and delete as in ArcCatalog.

1. ArcMap is the main application for data display, data query, data analysis, and data output. You can start ArcMap by clicking the ArcMap button in ArcCatalog or from the Programs menu. Start with a new blank map document. ArcMap organizes data sets into data frames (also called *maps*). You open a new data frame called Layers when you launch ArcMap. Right-click Layers, and select Properties. On the General tab, change the name Layers to Task 2 and click OK.
2. Next, add *emidalat* and *emidastrm.shp* to Task 2. Click the Add Data button in ArcMap, navigate to the Chapter 1 database, and select *emidalat* and *emidastrm.shp.* To select more than one data set to add, click the data sets while holding down the Ctrl key. An alternative to using the Add Data button is to use the drag-and-drop method, by dragging a dataset from the Catalog tree and dropping it in ArcMap's view window.
3. A warning message states that one or more layers are missing spatial reference information. Click OK to dismiss the dialog; *emidastrm.shp* does not have the projection information, although it is based on the UTM coordinate system, as is *emidalat*. You will learn in Chapter 2 how to define a coordinate system.
4. Both *emidastrm* and *emidalat* are highlighted in the table of contents, meaning that they are both active. You can deactivate them by clicking on the empty space. The table of contents has five tabs: List by Drawing Order, List by Source, List by Visibility, List by Selection, and Options. On the List by Drawing Order tab, you can change the drawing order of the layers by dragging and dropping a layer up or down. The List by Source tab shows the data source of each layer. The List by Visibility tab lets you turn on or off a layer in the data frame. The List by Selection tab lists the selectable layer(s). The Options button lets you change

the behavior and appearance of the table of contents. Return to List by Drawing Order.

Q2. Does ArcMap draw the top layer in the table of contents first?

5. The Standard toolbar in ArcMap has such tools as Zoom In, Zoom Out, Pan, Full Extent, Select Elements, and Identify. When you hold the mouse point over a tool, a message box appears with a description of the tool and its shortcut method.

6. ArcMap has two views: Data View and Layout View. (The buttons for the two views are located at the bottom of the view window.) Data View is for viewing data, whereas Layout View is for viewing the map product for printing and plotting. For this task, you will stay with Data View.

7. This step is to change the symbol for *emidastrm*. Click the symbol for *emidastrm* in the table of contents to open the Symbol Selector dialog. You can either select a preset symbol (e.g., river) or make up your own symbol for *emidastrm* by specifying its color and width or editing the symbol. Choose the preset symbol for river.

8. Next, classify *emidalat* into the elevation zones <900, 900–1000, 1000–1100, 1100–1200, 1200–1300, and >1300 meters. Right-click *emidalat*, and select Properties. On the Symbology tab, click Classified in the Show frame and click yes to build the histogram. Change the number of classes to 6, and click the Classify button. The Method dropdown list shows seven methods. Select Manual. There are two ways to set the break values for the elevation zones manually. To use the first method, click the first break line and drag it to a data value near 900. Then, set the other break lines near 1000, 1100, 1200, 1300, and 1337. To use the second method, which is normally preferred, click the first cell in the Break Values frame and enter 900. Then enter 1000, 1100, 1200, and 1300 for the next four cells. (If the break value you entered is changed to a different value, reenter it.) Use the second method to set the break values, and click OK to dismiss the Classification dialog. In the Layer Properties dialog, change the value ranges under Label to 855–900, 900–1,000, 1,000–1,100, 1,100–1,200, 1,200–1,300, and 1,300–1,337. (Remove the extra 0s in the decimal digits because they are distracting on the map.)

Q3. List the other classification methods besides Manual that are available in ArcMap.

9. You can change the color scheme for *emidalat* by using the Color Ramp dropdown list. Sometimes it is easier to select a color scheme using words instead of graphic views. In that case, you can right-click inside the Color Ramp box and uncheck Graphic View. The Color Ramp dropdown list now shows White to Black, Yellow to Red, and so on. Select Elevation #1. Click OK to dismiss the dialog.

10. This step lets you derive a slope layer from *emidalat*. Select Extensions from the Customize menu and check Spatial Analyst. Then click the ArcToolbox button to open ArcToolbox. The Slope tool resides in the Spatial Analyst Tools/Surface toolset. Double-click the Slope tool. In the Slope dialog, select *emidalat* for the input raster, save the output raster as *slope*, and click OK. *slope* is added to Task 2.

11. You can save Task 2 as a map document before exiting ArcMap. Select Save from the File menu in ArcMap. Navigate to the Chapter 1 database, enter *chap1* for the file name, and click Save. Data sets displayed in Task 2 are now saved with *chap1.mxd*. To re-open *chap1.mxd*, *chap1.mxd* must reside in the same folder as the data sets it references. You can save the map document at any time during a session so that you do not lose the work you have done in case of unexpected problems. You can also save a map document with the relative path name option (e.g., without the drive name). Select Map Document Properties from ArcMap's File menu. In the next dialog, check the box to store relative path names to data sources.

12. To make sure that *chap1.mxd* is saved correctly, first select Exit from ArcMap's File menu. Then launch ArcMap again. Click on chap1 or select *chap1.mxd* from the File menu.

Challenge Task

What you need: *menan-buttes*, an elevation raster.

This challenge question asks you to display *menan-buttes* in 10 elevation zones and save the map along with Task 2 in *chap1.mxd*.

1. Open *chap1.mxd*. Select Data Frame from ArcMap's Insert menu. Rename the new data frame Challenge, and add *menan-buttes* to Challenge. Challenge is in bold, meaning that it is active. (If it is not active, you can right click Challenge and select Activate.)

2. Display *menan-buttes* in 10 elevation zones by using the elevation #2 color ramp and the following break values: 4800, 4900, 5000, 5100, 5200, 5300, 5400, 5500, 5600, and 5619 (feet).

3. Save Challenge with Task 2 in *chap1.mxd*.

REFERENCES

Broome, F. R., and D. B. Meixler. 1990. The TIGER Data Base Structure. *Cartography and Geographic Information Systems* 17:39–47.

Butler, D. 2006. Virtual Globes: The Web-Wide World. *Nature* 439:776–778.

Chrisman, N. 1988. The Risks of Software Innovation: A Case Study of the Harvard Lab. *The American Cartographer* 15:291–300.

Coppock, J. T. 1988. The Analogue to Digital Revolution: A View from an Unreconstructed Geographer. *The American Cartographer* 15:263–75.

Crampton, J. W., M. Graham, A. Poorthuis, T. Shelton, M. Stephens, M. W. Wilson, and M. Zook. 2013. Beyond the Geotag: Situating "Big Data" and Leveraging the Potential of the Geoweb. *Cartography and Geographic Information Science* 40:130–39.

Crawford, K., and M. Finn. 2015. The Limits of Crisis Data: Analytical and Ethical Challenges of Using Social and Mobile Data to Understand Disasters. *GeoJournal* 80:491–502.

Goodchild, M. F. 2003. Geographic Information Science and Systems for Environmental Management. *Annual Review of Environment & Resources* 28:493–519.

Goodchild, M. F. 2007. Citizens as Sensors: The World of Volunteered Geography. *GeoJournal* 69:211–21.

Goodchild, M. F., and J. A. Glennon. 2010. Crowdsourcing Geographic Information for Disaster Response: A Research Frontier. *International Journal of Digital Earth* 3:231–41.

Hahmann, S., and D. Burghardt. 2013. How Much Information is Geospatially Referenced? Networks and Cognition. *International Journal of Geographical Information Science* 27: 1171–1189.

Haklay, M. 2010. How Good is Volunteered Geographical Information? A Comparative Study of OpenStreetMap and Ordnance Survey Datasets. *Environment and Planning B: Planning and Design* 37:682–703.

Haworth, B., and E. Bruce. 2015. A Review of Volunteered Geographic Information for Disaster Management. *Geography Compass* 9:237–50.

Kanza, Y., and H. Samet. 2015. An Online Marketplace for Geosocial Data. *Proceedings of the 23rd ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems,* Seattle, WA, November 2015.

Liu, S. B., and L. Palen. 2010. The new cartographers: Crisis map mashups and the emergence of neogeographic practice. *Cartography and Geographic Information Science* 37:69–90.

McDougall, K., and P. Temple-Watts. 2012. The Use of Lidar and Volunteered Geographic Information to Map Flood Extents and Inundation. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Science,* I-4:251–56.

McHarg, I. L. 1969. *Design with Nature.* New York: Natural History Press.

Meier, P. 2012. Crisis Mapping in Action: How Open Source

Software and Global Volunteer Networks Are Changing the World, One Map at a Time. *Journal of Map and Geography Libraries* 8:89–100.

Neis, P., and D. Zielstra. 2014. Recent Developments and Future Trends in Volunteered Geographic Information Research: The Case of OpenStreetMap. *Future Internet* 6:76–106; doi:10.3390/fi6010076.

Quinn, S., and L. Yapa. 2016. OpenStreetMap and Food Security: A Case Study in the City of Philadelphia. *The Professional Geographer* 68:271–80.

Rhind, D. 1988. Personality as a Factor in the Development of a Discipline: The Example of Computer-Assisted Cartography. *The American Cartographer* 15:277–89.

Shelton, T., A. Poorthuis, M. Graham, and M. Zook. 2014. Mapping the Data Shadows of Hurricane Sandy: Uncovering the Sociospatial Dimensions of "Big Data." *Geoforum* 52:167–79.

Steiniger, S., and A. J. S. Hunter. 2012. Free and Open Source GIS Software for Building a Spatial Data Infrastructure. In E. Bocher and M. Neteler, eds., *Geospatial Free and Open Source Software in the 21th Century*, pp. 247–61. Berlin: Springer.

Sui, D., and M. Goodchild. 2011. The Convergence of GIS and Social Media: Challenges for GIScience. International Journal of Geographical Information Science 25:1737–1748.

Tomlinson, R. F. 1984. Geographic Information Systems: The New Frontier. *The Operational Geographer* 5:31–35.

Wright, D. J., M. F. Goodchild, and J. D. Proctor. 1997. Demystifying the Persistent Ambiguity of GIS as "Tool" versus "Science." *Annals of the Association of American Geographers* 87:346–62.

Zook, M., M. Graham, T. Shelton, and S. Gorman. 2010. Volunteered Geographic Information and Crowdsourcing Disaster Relief: A Case Study of the Haitian Earthquake. *World Medical & Health Policy* 2:7–33.

Design Elements: (Compass): DNY59/Getty Images; (Mississippi River): Landsat image by Robert Simmon, based on data from the UMD Global Land Cover Facility/NASA

2

Coordinate Systems

Chapter Outline

A basic principle in geographic information system (GIS) is that map layers to be used together must align spatially. Obvious mistakes can occur if they do not. For example, Figure 2.1 shows the interstate highway maps of Idaho and Montana downloaded separately from the Internet. The two maps do not register spatially. To connect the highway networks across the shared state border, we must convert them to a common spatial reference system. Chapter 2 deals with coordinate systems, which provide the spatial reference.

GIS users typically work with map features on a plane (flat surface). These map features represent spatial features on the Earth's surface. The locations of map features are based on a plane coordinate system expressed in *x*- and *y*-coordinates, whereas the locations of spatial features on the Earth's surface are based on a geographic coordinate system expressed in longitude and latitude values. A map projection bridges the two types of coordinate systems. The process of projection transforms the Earth's surface to a plane, and the outcome is a map projection, ready to be used for a projected coordinate system.

We regularly download data sets, both vector and raster, from the Internet for GIS projects. Some digital data sets are measured in longitude and latitude values, whereas others are in different projected coordinate systems. It is a good idea to process these data sets at the start of a project so that

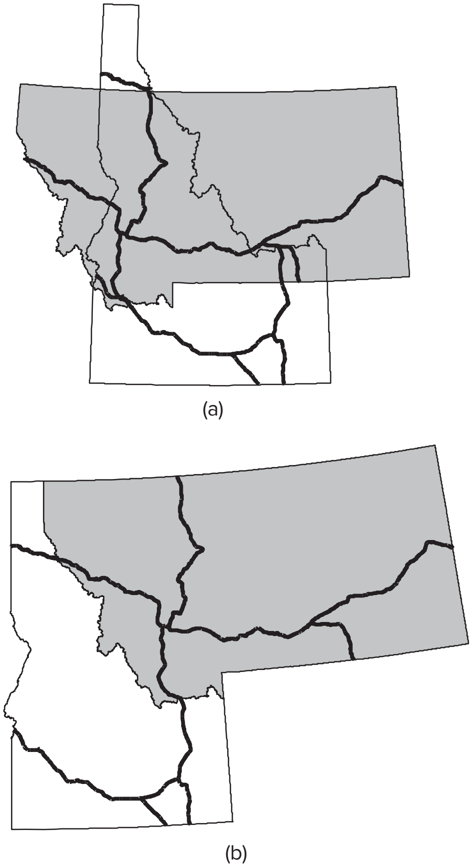

Figure 2.1
The top map shows the interstate highways in Idaho and Montana based on different coordinate systems. The bottom map shows the connected interstate networks based on the same coordinate system.

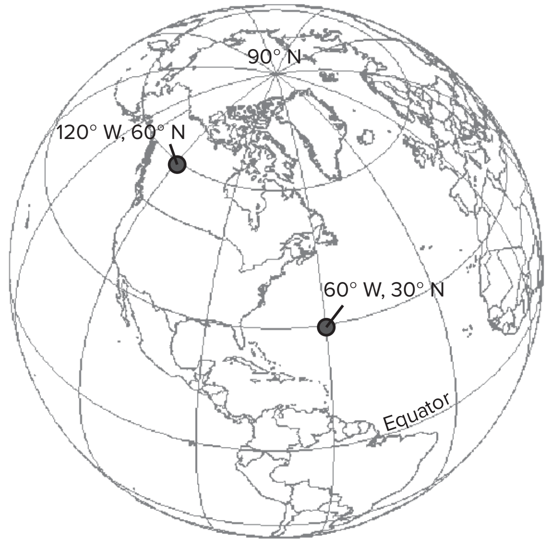

Figure 2.2
The geographic coordinate system.

they are on a common coordinate system. Processing in this case means projection and reprojection. **Projection** converts data sets from geographic coordinates to projected coordinates, and **reprojection** converts from one system of projected coordinates to another system. Typically, projection and reprojection are among the initial tasks performed in a GIS project.

Chapter 2 is divided into the following five sections. Section 2.1 describes the geographic coordinate system. Section 2.2 discusses projection, types of map projections, and map projection parameters. Sections 2.3 and 2.4 cover commonly used map projections and coordinate systems, respectively. Section 2.5 discusses how to work with coordinate systems in a GIS package.

2.1 GEOGRAPHIC COORDINATE SYSTEM

The **geographic coordinate system** is the reference system for locating spatial features on the Earth's surface (Figure 2.2). The geographic coordinate system is defined by **longitude** and **latitude**. Both longitude and latitude are angular measures: longitude measures the angle east or west from the prime meridian, and latitude measures the angle north or south of the equatorial plane. In Figure 2.3, for example, the longitude at point X is the angle *a* west of the prime meridian, and the latitude at point Y is the angle *b* north of the equator.

Meridians are lines of equal longitude. The prime meridian passes through Greenwich, England, and has the reading of 0°. Using the prime meridian as a reference, we can measure the longitude value

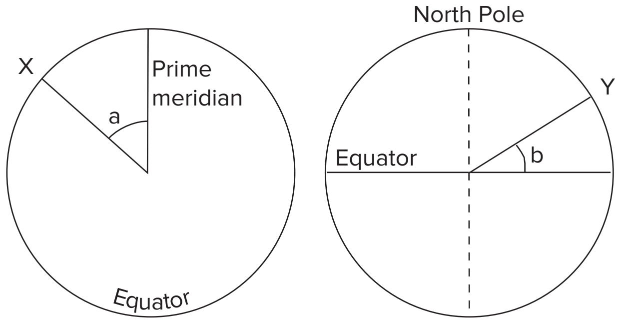

Figure 2.3
A longitude reading at point X is represented by a on the left, and a latitude reading at Y is represented by *b* on the right. Both longitude and latitude readings are angular measures.

of a point on the Earth's surface as 0° to 180° east or west of the prime meridian. Meridians are therefore used for measuring location in the E–W direction. **Parallels** are lines of equal latitude. Using the equator as 0° latitude, we can measure the latitude value of a point as 0° to 90° north or south of the equator. Parallels are therefore used for measuring location in the N–S direction. A point location denoted by (120° W, 60° N) means that it is 120° west of the prime meridian and 60° north of the equator.

The prime meridian and the equator serve as the baselines of the geographic coordinate system. The notation of geographic coordinates is therefore like plane coordinates: longitude values are equivalent to *x* values and latitude values are equivalent to y values. And, as with *x*-, *y*-coordinates, it is conventional in GIS to enter longitude and latitude values with positive or negative signs. Longitude values are positive in the eastern hemisphere and negative in the western hemisphere. Latitude values are positive if north of the equator, and negative if south of the equator.

The angular measures of longitude and latitude may be expressed in **degrees-minutes-seconds (DMS), decimal degrees (DD),** or radians (rad). Given that 1 degree equals 60 minutes and 1 minute equals 60 seconds, we can convert between DMS and DD. For example, a latitude value of 45°52′30″ would be equal to 45.875° (45 + 52/60 + 30/3600). Radians are typically used in computer programs. One radian equals 57.2958°, and one degree equals 0.01745 rad.

2.1.1 Approximation of the Earth

Viewed from space, the Earth looks like a perfect sphere. But it is not because the Earth is wider along the equator than between the poles. An approximation of the shape and size of the Earth is an oblate spheroid, also called **ellipsoid,** an ellipse rotated about its minor axis (Kjenstad 2011).

An ellipsoid approximating the Earth has its major axis *(a)* along the equator and its minor axis *(b)* connecting the poles (Figure 2.4). A parameter called the *flattening (f),* defined by $(a - b)/a$, measures the difference between the two axes of an ellipsoid. Geographic coordinates based on an ellipsoid are known as geodetic coordinates, which are the basis for all

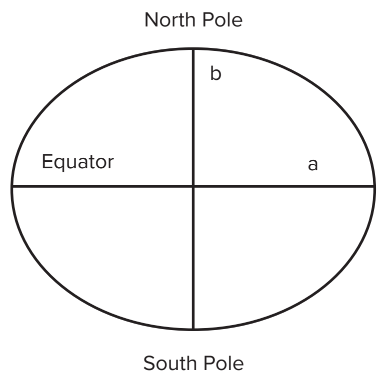

Figure 2.4
The flattening is based on the difference between the semimajor axis *a* and the semiminor axis *b*.

mapping systems (Iliffe 2000). In this book, we will use the generic term *geographic coordinates*.

2.1.2 Datum

A **datum** is a mathematical model of the Earth, which serves as the reference or base for calculating the geographic coordinates in the case of a horizontal datum and for calculating elevations in the case of a vertical datum (Burkard 1984; Moffitt and Bossler 1998). Horizontal datum is considered in this chapter and vertical datum in Chapter 5. The definition of a horizontal datum consists of the longitude and latitude of an initial point (origin), an ellipsoid, and the separation of the ellipsoid and the Earth at the origin. Datum and ellipsoid are therefore closely related.

To attain a better fit of the Earth locally, many countries developed their own datums in the past. Among these local datums are the European Datum, the Australian Geodetic Datum, the Tokyo Datum, and the Indian Datum (for India and several adjacent countries). In the United States, GIS users have been using **NAD27** (North American Datum of 1927) and **NAD83** (North American Datum of 1983).

2.1.3 NAD27 and NAD83

NAD27 is a local datum based on the **Clarke 1866** ellipsoid, a ground-measured ellipsoid with its origin at Meades Ranch in Kansas. Hawaii was the only state that did not actually adopt NAD27; Hawaii used the Old Hawaiian Datum, an independent datum based on a different origin from that of NAD27. Clarke 1866's semimajor axis (equatorial radius) and semiminor axis (polar radius) measure 6,378,206 meters (3963 miles) and 6,356,584 meters (3949 miles), respectively, with the flattening of 1/294.98 (Burkard 1984).

In 1986, the National Geodetic Survey (NGS) introduced NAD83 based on the **GRS80** ellipsoid. GRS80's semimajor axis and semiminor axis measure 6,378,137 meters (3963 miles) and 6,356,752 meters (3950 miles), respectively, with the flattening of 1/298.26 (Burkard 1984). The shape and size of the Earth for GRS80 were determined through measurements made by Doppler satellite observations. Unlike NAD27, NAD83 is a geocentric datum referenced to the center of the Earth's mass.

Datum shift from NAD27 to NAD83 can result in substantial shifts of point positions. As shown in Figure 2.5, horizontal shifts are between

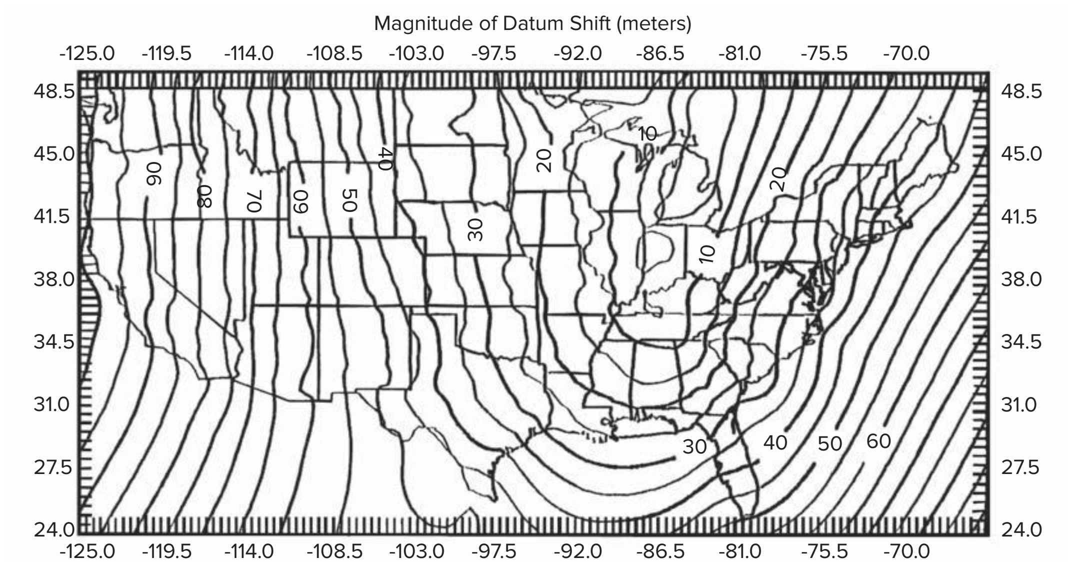

Figure 2.5
The isolines show the magnitudes of the horizontal shift from NAD27 to NAD83 in meters. See Section 2.1.2 for the definition of the horizontal shift. (By permission of the National Geodetic Survey.)

10 and 100 meters in the conterminous United States. (The shifts are more than 200 meters in Alaska and in excess of 400 meters in Hawaii.) For example, for the Ozette quadrangle map from the Olympic Peninsula in Washington, the shift is 98 meters to the east and 26 meters to the north. The horizontal shift is, therefore, 101.4 meters ($\sqrt{98^2 + 26^2}$). With this kind of datum shift, it is clear that digital layers based on different datums will not register correctly. To transform from one datum to another, commonly called *datum transformation* or *geographic transformation*, requires re-computing longitude and latitude values using a software package. For example, NADCON is a software package that can be downloaded at the NGS website for conversion between NAD27 and NAD83.

The original NAD83 used Doppler satellite observations to estimate the Earth's shape and size. Since then, several realizations (updates) of NAD83 have been made with improved accuracy. In the late 1980s, the NGS began a program of using GPS technology to establish the High Accuracy Reference Network (HARN) on a state-by-state basis. In 1994, the NGS started the Continuously Operating Reference Stations (CORS) network, a network of over 200 stations that provide measurements for the post-processing of GPS data. The positional difference of a control point may be up to a meter between the original NAD83 and HARN but less than 10 centimeters between HARN and CORS (Snay and Soler 2000). In 2007, the National Spatial Reference System (NSRS) was completed by the NGS for the purpose of resolving inconsistencies between HARN and CORS and also between states. The current and the fourth realization of NAD83 is the National Adjustment of 2011 project completed in 2012. The process of updating and improving the official horizontal datum in the United States will continue in the future (Box 2.1). According to the NGS ten-year plan (2013-2023), NAD83 will be replaced in 2022 **(http://www.ngs.noaa.gov/web/news/Ten_Year_Plan_2013-2023.pdf).**

To distinguish the original NAD83 and its subsequent four realizations, a GIS package uses the notations of NAD83, NAD83(HARN), NAD83(CORS96), NAD83(NSRS2007), and NAD83(2011). Additionally, NAD83(CSRS) is a realization of NAD83 used in Canada, with CSRS standing for the Canadian Spatial Reference System.

Box 2.1 Datum Accuracy

A spatial reference system requires a datum. Datum accuracy is therefore an important topic in mapping. NAD27 was based on surveys of approximately 26,000 stations, with latitude and longitude coordinates collected at each station. To improve the accuracy of NAD27, NAD83 used a total of 250,000 stations by combining those stations from NAD27 and additional positions measured from Doppler satellite data. The subsequent updates of NAD83 have relied on GPS technology to identify locations on the Earth's surface and incorporate them into NAD83. Each new datum represents an improved accuracy in locating points on the geographic coordinate system. This improved accuracy is important in marking land parcel boundaries, constructing roads and pipelines, and many other tasks. For many GIS users, however, datum shift is probably more important than datum accuracy. This is because a GIS project tends to involves layers from different sources, which may be based on different datums. Unless a datum or geographic transformation is made, these layers will not register correctly.

2.1.4 WGS84

WGS84 (World Geodetic System 1984) is used by the U.S. Department of Defense as a global reference system for supporting positioning and navigation (True 2004). It is the datum for GPS readings. The satellites used by GPS send their positions in WGS84 coordinates, and all calculations internal to GPS receivers are also based on WGS84.

The original WGS84 was established in 1987 using Doppler satellite observations; therefore, the original WGS84 is identical to the original NAD83 in North America. Since 1987, WGS84 has been readjusted using GPS data. A total of five realizations were made between 1994 and 2013 by taking advantage of new data and methods to improve its accuracy. Also, through these realizations, WGS84 has aligned with the International Terrestrial Reference Frame (ITRF), a world spatial reference system: WGS84(G730) with ITRF91, WGS84(G873) with ITRF94, WGS84(G1150) with ITRF2000, WGS84(G1674) with ITRF2008, and WGS84(G1762) with ITRF2008.

2.2 MAP PROJECTIONS

A **map projection** transforms the geographic coordinates on an ellipsoid into locations on a plane. The outcome of this transformation process is a systematic arrangement of parallels and meridians on a flat surface representing the geographic coordinate system.

A map projection provides a couple of distinctive advantages. First, a map projection allows us to use two-dimensional maps, either paper or digital. Second, a map projection allows us to work with plane coordinates rather than longitude and latitude values. Computations with geographic coordinates are more complex (Box 2.2).

But the transformation from the surface of an ellipsoid to a flat surface always involves distortion, and no map projection is perfect. This is why hundreds of map projections have been developed for mapmaking (Maling 1992; Snyder 1993). Every map projection preserves certain spatial properties while sacrificing other properties.

Box 2.2 How to Measure Distances on the Earth's Surface

The equation for measuring distances on a plane coordinate system is:

$$D = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

where x_i and y_i are the coordinates of point *i*.

This equation, however, cannot be used for measuring distances on the Earth's surface. Because meridians converge at the poles, the length of 1-degree latitude does not remain constant but gradually decreases from the equator to 0 at the pole. The standard and simplest method for calculating the shortest distance between two points on the Earth's surface, also called geodesic distance, uses the equation:

$$\cos(d) = \sin(a)\sin(b) + \cos(b) + \cos(c)$$

where d is the angular distance between points A and B in degrees, a is the latitude of A, b is the latitude of B, and c is the difference in longitude between A and B. To convert d to a linear distance measure, one can multiply d by the length of 1 degree at the equator, which is 111.32 kilometers or 69.17 miles. This method is accurate unless d is very close to zero (Snyder 1987).

Most data producers deliver spatial data in geographic coordinates to be used with any projected coordinate system the end user needs to work with. But more GIS users are using spatial data in geographic coordinates directly for data display and even simple analysis. Distance measurements from such spatial data are usually derived from the shortest spherical distance between points.

2.2.1 Types of Map Projections

Map projections can be grouped by either the preserved property or the projection surface. Cartographers group map projections by the preserved property into the following four classes: conformal, equal area or equivalent, equidistant, and azimuthal or true direction. A **conformal projection** preserves local angles and shapes. An **equivalent projection** represents areas in correct relative size. An **equidistant projection** maintains consistency of scale along certain lines. And an **azimuthal projection** retains certain accurate directions. The preserved property of a map projection is often included in its name, such as the Lambert conformal conic projection or the Albers equal-area conic projection.

The conformal and equivalent properties are mutually exclusive. Otherwise a map projection can have more than one preserved property, such as conformal and azimuthal. The conformal and equivalent properties are global properties, meaning that they apply to the entire map projection. The equidistant and azimuthal properties are local properties and may be true only from or to the center of the map projection.

The preserved property is important for selecting an appropriate map projection for thematic mapping (Battersby 2009). For example, a population map of the world should be based on an equivalent projection. By representing areas in correct size, the population map can create a correct impression of population densities. In contrast, an equidistant projection would be better for mapping the distance ranges from a telecommunication tower.

Cartographers often use a geometric object and a globe to illustrate how to construct a map projection. For example, by placing a cylinder tangent to a lighted globe, one can draw a projection by tracing the lines of longitude and latitude onto the cylinder. The cylinder is the projection surface or the developable surface, and the globe is the **reference globe.** Other common projection surfaces include a cone and a plane. Therefore, map projections can be grouped by their projection surfaces into cylindrical, conic, and azimuthal. A map projection is called a **cylindrical projection** if it can be constructed using a cylinder, a **conic projection** if using a cone, and an **azimuthal projection** if using a plane.

The use of a geometric object helps explain two other projection concepts: case and aspect. For a conic projection, the cone can be placed so that it is tangent to the globe or intersects the globe (Figure 2.6). The first is the simple case, which results in one line of tangency, and the second is the secant case, which results in two lines of tangency. A cylindrical projection behaves the same way as a conic projection in terms of case. An azimuthal projection, on the other hand, has a point of tangency in the simple case and a line of tangency in the secant case. Aspect describes the placement of a geometric object relative to a globe. A plane, for example, may be tangent at any point on a globe. A polar aspect refers to tangency at the pole, an equatorial aspect at the equator, and an oblique

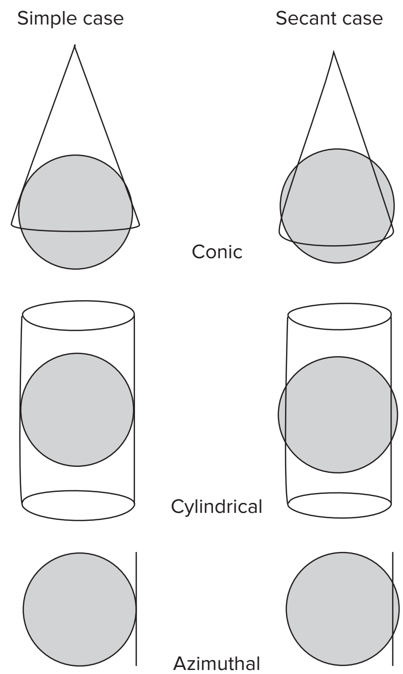

Figure 2.6
Case and projection.

aspect anywhere between the equator and the pole (Figure 2.7).

2.2.2 Map Projection Parameters

A map projection is defined by its parameters. Typically, a map projection has five or more parameters. A **standard line** refers to the line of tangency between the projection surface and the reference globe. For cylindrical and conic projections the simple case has one standard line, whereas the secant case has two standard lines. The standard line is called the **standard parallel** if it follows a parallel, and the **standard meridian** if it follows a meridian.

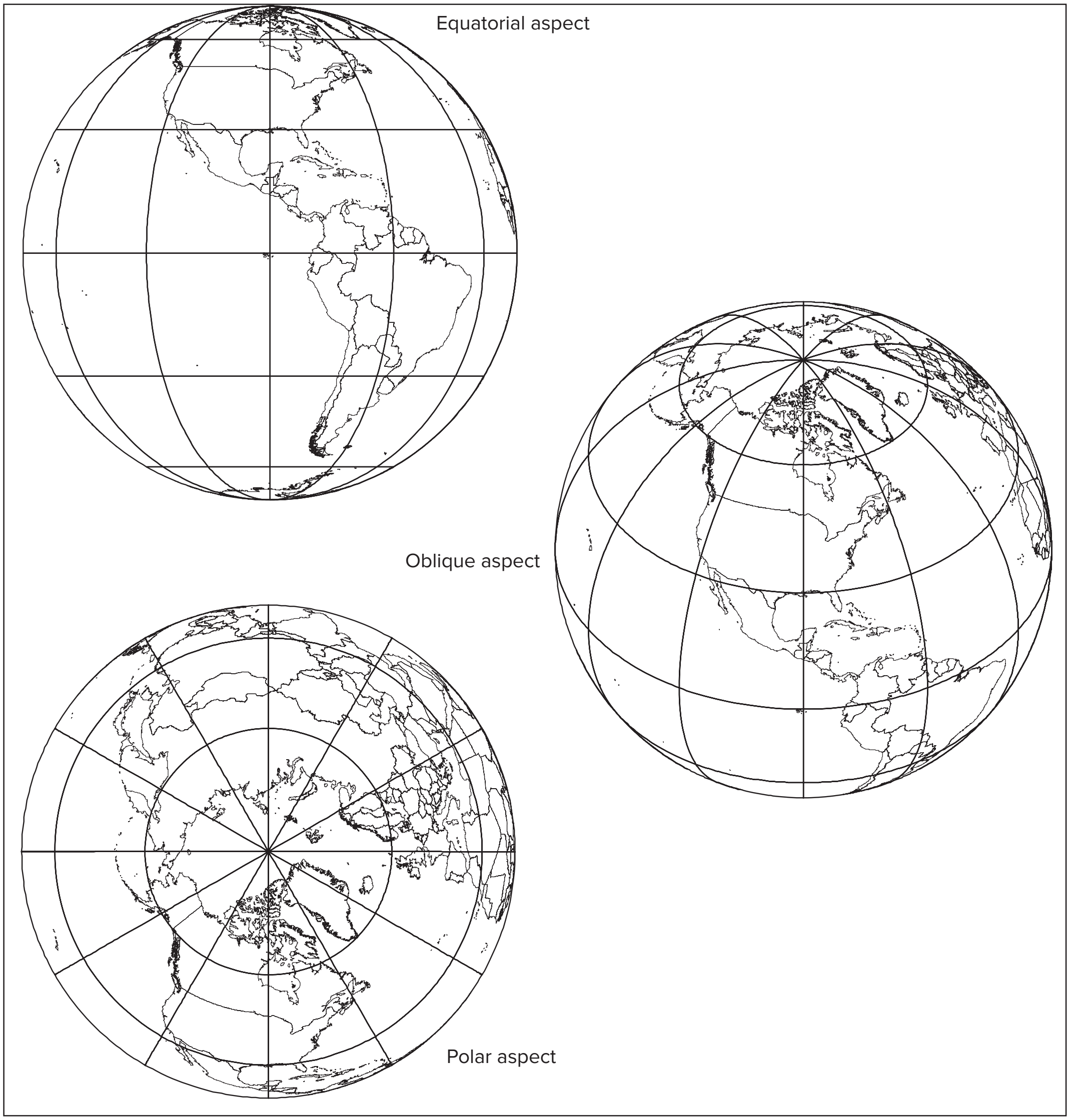

Figure 2.7
Aspect and projection.

Because the standard line is the same as on the reference globe, it has no distortion from the projection process. Away from the standard line, projection distortion can result from tearing, shearing, or compression of the spherical surface to meet the projection surface. A common measure of projection distortion is scale, which is defined as the ratio of a distance on a map (or globe) to its corresponding ground distance. The **principal scale,** or the scale of the reference globe, can therefore be derived from the ratio of the globe's radius to the Earth's radius (3963 miles or 6378 kilometers). For example, if a globe's radius is 12 inches, then the principal scale is 1:20,924,640 (1:3963 × 5280).

The principal scale applies only to the standard line in a map projection. This is why the standard parallel is sometimes called the latitude of true scale. The local scale applies to other parts of the map projection. Depending on the degree of distortion, the local scale can vary across a map projection (Bosowski and Feeman 1997). The **scale factor** is the normalized local scale, defined as the ratio of the local scale to the principal scale. The scale factor is 1 along the standard line and becomes either less than 1 or greater than 1 away from the standard line.

The standard line should not be confused with the central line: the standard line dictates the distribution pattern of projection distortion, whereas the **central lines** (the central parallel and meridian) define the center of a map projection. The central parallel, sometimes called the latitude of origin, often differs from the standard parallel. Likewise, the central meridian often differs from the standard meridian. A good example for showing the difference between the central meridian and the standard line is the transverse Mercator projection. Normally a secant projection, a transverse Mercator projection is defined by its central meridian and two standard lines on either side. The standard line has a scale factor of 1, and the central meridian has a scale factor of less than 1 (Figure 2.8).

When a map projection is used as the basis of a coordinate system, the center of the map projection, as defined by the central parallel and the central meridian, becomes the origin of the coordinate system and divides the coordinate system into four quadrants. The *x*-, *y*-coordinates of a point are either positive or negative, depending on where the point is located (Figure 2.9). To avoid having negative coordinates, we can assign *x*-, *y*-coordinate values to the origin of the coordinate system. The **false easting** is

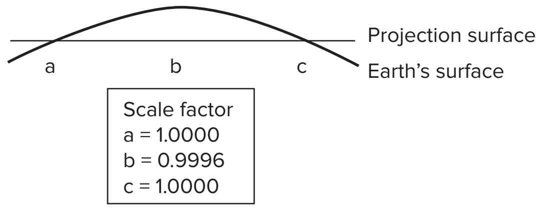

Figure 2.8
In this secant case transverse Mercator projection, the central meridian at *b* has a scale factor of 0.9996, because it deviates from the projection surface, meaning that it has projection distortion. The two standard lines at *a* and *c*, on either side of the central meridian, have a scale factor of 1.0. Section 2.4.1 covers the use of the secant case transverse Mercator projection.

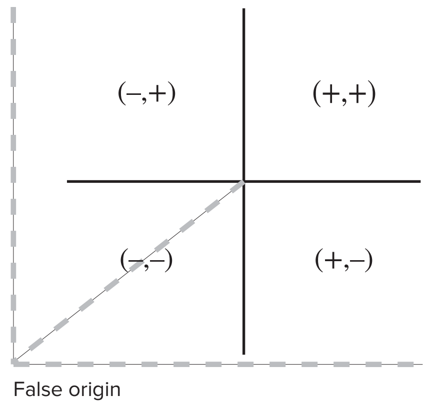

Figure 2.9
The central parallel and the central meridian divide a map projection into four quadrants. Points within the NE quadrant have positive *x*- and *y*-coordinates, points within the NW quadrant have negative *x*-coordinates and positive *y*-coordinates, points within the SE quadrant have positive *x*-coordinates and negative *y*-coordinates, and points within the SW quadrant have negative *x*- and *y*-coordinates. The purpose of having a false origin is to place all points within the NE quadrant of the false origin so that the points all have positive *x*- and *y*-coordinates.

the assigned x-coordinate value and the **false northing** is the assigned y-coordinate value. Essentially, the false easting and false northing create a false origin so that all points fall within the NE quadrant and have positive coordinates (Figure 2.9).

2.3 Commonly Used Map Projections

Hundreds of map projections are in use. Commonly used map projections in GIS are not necessarily the same as those we see in classrooms or in magazines. For example, the Robinson projection is a popular projection for general mapping at the global scale because it is aesthetically pleasing (Jenny, Patterson, and Hurni 2010). But the Robinson projection may not be suitable for GIS applications. A map projection for GIS applications usually has one of the preserved properties mentioned earlier, especially the conformal property. Because it preserves local shapes and angles, a conformal projection allows adjacent maps to join correctly at the corners. This is important in developing a map series such as the U.S. Geological Survey (USGS) quadrangle maps.

2.3.1 Transverse Mercator

The **transverse Mercator projection,** a secant cylindrical projection also known as the Gauss-Kruger, is a well-known projection for mapping the world. It is a variation of the Mercator projection, but the two look different (Figure 2.10). The Mercator projection uses the standard parallel, whereas the

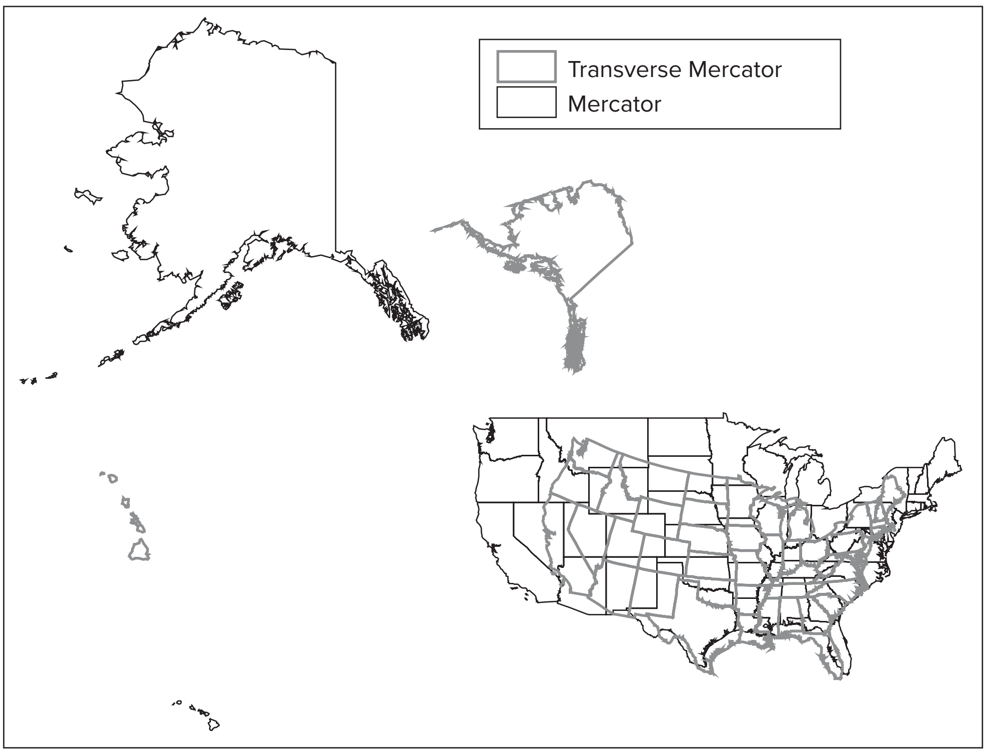

Figure 2.10
The Mercator and the transverse Mercator projection of the United States. For both projections, the central meridian is 90° W and the latitude of true scale is the equator.

transverse Mercator projection uses the standard meridian. Both projections are conformal.

The transverse Mercator is the basis for two common coordinate systems to be discussed in Section 2.4. The definition of the projection requires the following parameters: scale factor at central meridian, longitude of central meridian, latitude of origin (or central parallel), false easting, and false northing.

2.3.2 Lambert Conformal Conic

The **Lambert conformal conic projection** is a standard choice for mapping a midlatitude area of greater east–west than north–south extent, such as the state of Montana or the conterminous United States (Figure 2.11). The USGS has used the Lambert conformal conic for many topographic maps since 1957.

Typically a secant conic projection, the Lambert conformal conic is defined by the following parameters: first and second standard parallels, central meridian, latitude of projection's origin, false easting, and false northing.

2.3.3 Albers Equal-Area Conic

The Albers equal-area conic projection has the same parameters as the Lambert conformal conic projection. In fact, the two projections are quite similar except that one is equal area and the other is conformal. The Albers equal-area conic is the projection for national land cover data for the conterminous United States (Chapter 4).

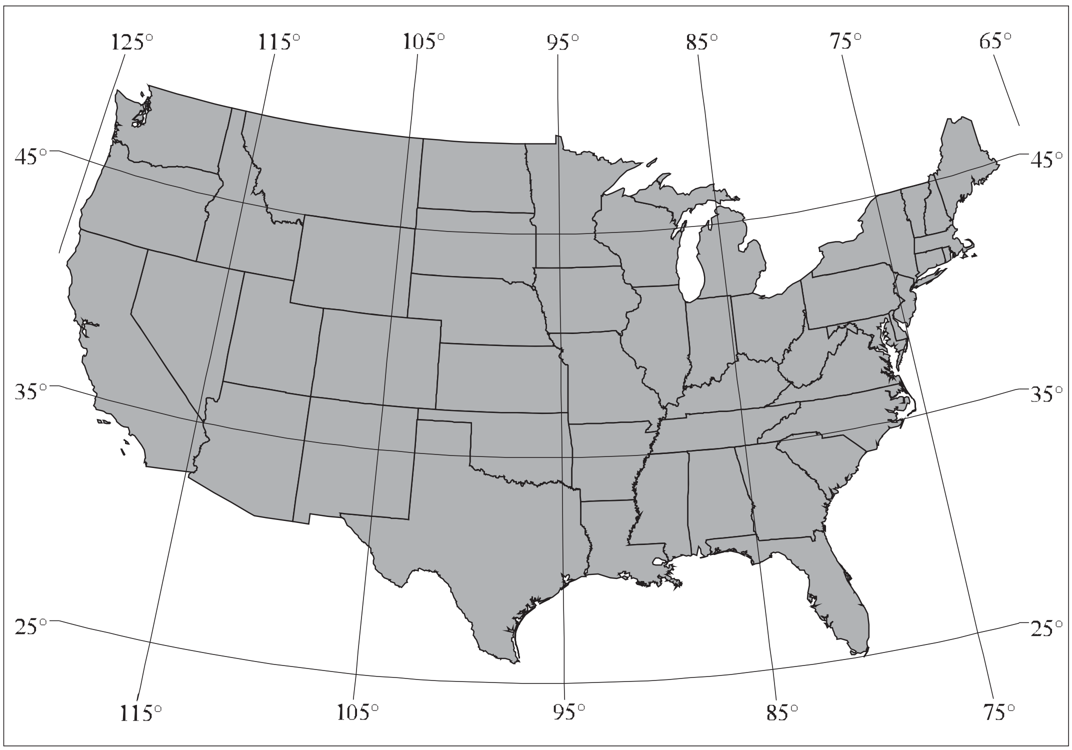

Figure 2.11
The Lambert conformal conic projection of the conterminous United States. The central meridian is 96° W, the two standard parallels are 33° N and 45° N, and the latitude of projection's origin is 39° N.

2.3.4 Equidistant Conic

The equidistant conic projection is also called the simple conic projection. The projection preserves the distance property along all meridians and one or two standard parallels. It uses the same parameters as the Lambert conformal conic.

2.3.5 Web Mercator

Unlike the transverse Mercator, as well as other projections covered in the previous sections, which were all invented before the end of the eighteenth century (Snyder 1993), the Web Mercator projection is a new invention, probably made popular by Google Maps in 2005 (Battersby et al. 2014). It has since become the standard projection for online mapping, as Google Maps, Bing Maps, MapQuest, and ArcGIS Online all use it in their mapping systems. What is Web Mercator? It is a special case of the Mercator on a sphere and projected from latitude and longitude coordinates from the WGS84 ellipsoid (Battersby et al. 2014). A main advantage of using a sphere is that it simplifies the calculations. Also, because it is a conformal projection, the Web Mercator projection preserves local angles and shapes and has north at the top of the map. However, like the Mercator, the Web Mercator projection has area and distance distortions, especially in high latitude areas. A GIS package has tools for reprojecting Web Mercator to other projections and vice versa.

2.4 PROJECTED COORDINATE SYSTEMS

A **projected coordinate system** is built on a map projection. Projected coordinate systems and map projections are often used interchangeably. For example, the Lambert conformal conic is a map projection but it can also refer to a coordinate system. In practice, however, projected coordinate systems are designed for detailed calculations and positioning, and are typically used in large-scale mapping such as at a scale of 1:24,000 or larger (Box 2.3). Accuracy in a feature's location and its position relative to other features is therefore a key consideration in the design of a projected coordinate system.

To maintain the level of accuracy desired for measurements, a projected coordinate system is often divided into different zones, with each zone defined by a different projection center. Moreover, a projected coordinate system is defined not only by the parameters of the map projection it is based

Box 2.3 Map Scale

Map scale is the ratio of the map distance to the corresponding ground distance. This definition applies to different measurement units. A 1:24,000 scale map can mean that a map distance of 1 centimeter represents 24,000 centimeters (240 meters) on the ground. A 1:24,000 scale map can also mean that a map distance of 1 inch represents 24,000 inches (2000 feet) on the ground. Regardless of its measurement unit, 1:24,000 is a larger map scale than 1:100,000 and the same spatial feature (e.g., a town) appears larger on a 1:24,000 scale map than on a 1:100,000 scale map. Some cartographers consider maps with a scale of 1:24,000 or larger to be large-scale maps.

Map scale should not be confused with spatial scale, a term commonly used in natural resource management. Spatial scale refers to the size of area or extent. Unlike map scale, spatial scale is not rigidly defined. A large spatial scale simply means that it covers a larger area than a small spatial scale. A large spatial scale to an ecologist is, therefore, a small map scale to a cartographer.

on but also the parameters of the geographic coordinate system (e.g., datum) that the map projection is derived from.

Three coordinate systems are commonly used in the United States: the Universal Transverse Mercator (UTM) grid system, the Universal Polar Stereographic (UPS) grid system, and the State Plane Coordinate (SPC) system. This section also includes the Public Land Survey System (PLSS), a land partitioning system used in the United States for land parcel mapping. Although it is not a coordinate system, the PLSS is covered here as an example of a locational reference system that can be used for the same purpose as a coordinate system. Additional readings on these systems can be found in Robinson et al. (1995) and Kimerling et al. (2011).

2.4.1 The Universal Transverse Mercator Grid System

Used worldwide, the **UTM grid system** divides the Earth's surface between 84° N and 80° S into 60 zones. Each zone covers 6° of longitude and is numbered sequentially with zone 1 beginning at 180° W. Each zone is further divided into the northern and southern hemispheres. The designation of a UTM zone therefore carries a number and a letter. For example, UTM Zone 10N refers to the zone between 126° W and 120° W in the northern hemisphere. The inside of this book's back cover has a list of the UTM zone numbers and their longitude ranges. Figure 2.12 shows the UTM zones in the conterminous United States.

Because datum is part of the definition of a projected coordinate system, the UTM grid system may be based on NAD27, NAD83, or WGS84. Thus, if UTM Zone 10N is based on NAD83, then its full designation reads NAD 1983 UTM Zone 10N.

Each UTM zone is mapped onto a secant case transverse Mercator projection, with a scale factor of 0.9996 at the central meridian and the equator as the latitude of origin. The standard meridians are 180 kilometers to the east and the west of the central meridian (Figure 2.13). The use of a projection per UTM zone is designed to maintain the accuracy of at least one part in 2500 (i.e., distance measured over a 2500-meter course on the UTM grid system would be accurate within a meter of the true measure) (Kimerling et al. 2011).

In the northern hemisphere, UTM coordinates are measured from a false origin located at

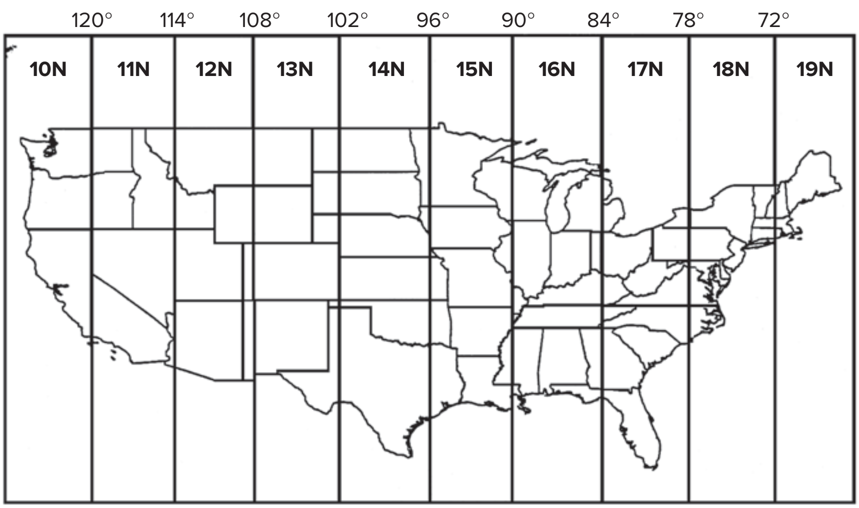

Figure 2.12
UTM zones range from zone 10N to 19N in the conterminous United States.

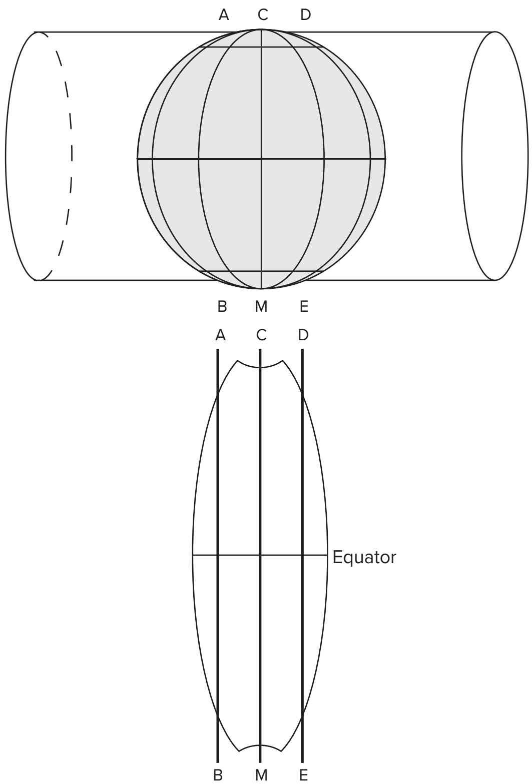

Figure 2.13
A UTM zone represents a secant case transverse Mercator projection. CM is the central meridian, and AB and DE are the standard meridians. The standard meridians are placed 180 kilometers west and east of the central meridian. Each UTM zone covers 6° of longitude and extends from 84° N to 80° S. The size and shape of the UTM zone are exaggerated for illustration purposes.

the equator and 500,000 meters west of the UTM zone's central meridian. In the southern hemisphere, UTM coordinates are measured from a false origin located at 10,000,000 meters south of the equator and 500,000 meters west of the UTM zone's central meridian.

The use of the false origins means that UTM coordinates are all positive but can be very large numbers. For example, the NW corner of the Moscow East, Idaho, quadrangle map has the UTM coordinates of 500,000 and 5,177,164 meters. To preserve data precision for computations with coordinates, we can apply ***x*-shift** and ***y*-shift** values to all coordinate readings to reduce the number of digits. For example, if the *x*-shift value is set as −500,000 meters and the *y*-shift value as −5,170,000 meters for the previous quadrangle map, the coordinates for its NW corner become 0 and 7164 meters. Small numbers such as 0 and 7164 reduce the chance of having truncated computational results. Like false easting and false northing, *x*-shift and *y*-shift change the values of *x*-, *y*-coordinates in a data set. They must be documented along with the projection parameters in the metadata (information about data, Chapter 5).

2.4.2 The Universal Polar Stereographic Grid System

The **UPS grid system** covers the polar areas. The stereographic projection is centered on the pole and is used for dividing the polar area into a series of 100,000-meter squares, similar to the UTM grid system. The UPS grid system can be used in conjunction with the UTM grid system to locate positions on the entire Earth's surface.

2.4.3 The State Plane Coordinate System

The **SPC system** was developed in the 1930s to permanently record original land survey monument locations in the United States. To maintain the required accuracy of one part in 10,000 or less, a state may have two or more SPC zones. As examples, Oregon has the North and South SPC zones and Idaho has the West, Central, and East SPC zones (Figure 2.14). Each SPC zone is mapped onto a map projection. Zones that are elongated in the north–south direction (e.g., Idaho's SPC zones) use the transverse Mercator and zones that are elongated in the east–west direction (e.g., Oregon's SPC zones) use the Lambert conformal conic. Some states (e.g., Florida and New York) use both the tranverse Mercator and Lambert conformal conic, and Alaska also uses the oblique Mercator to cover one zone for its panhandle. Point locations within each SPC zone are measured from a false origin located to the southwest of the zone.

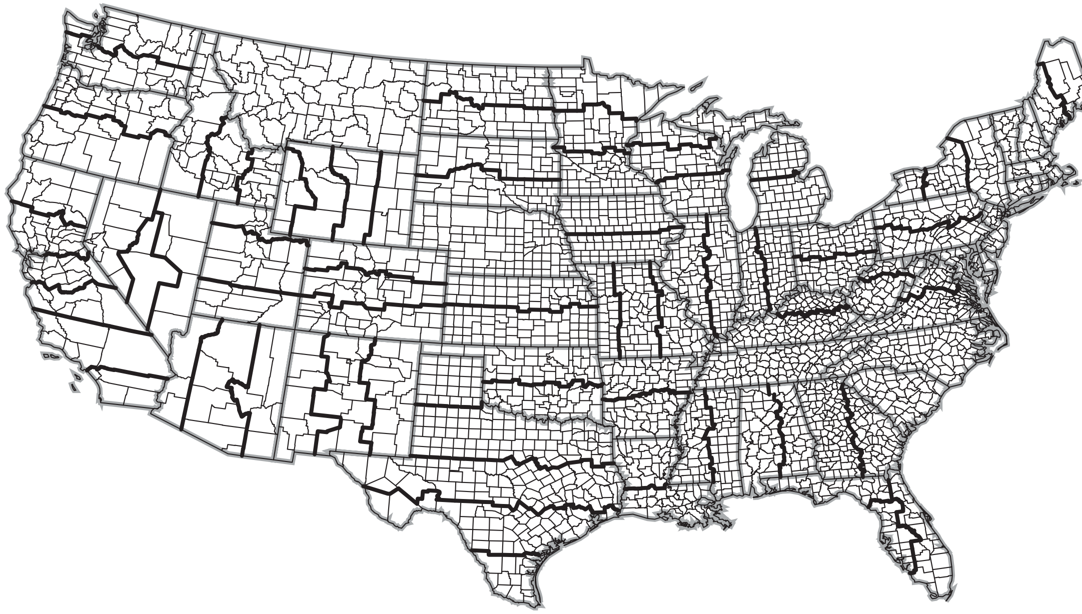

Figure 2.14
SPC83 zones in the conterminous United States. The thin lines are county boundaries, and the bold lines are SPC zone boundaries. This map corresponds to the SPC83 table on the inside of this book's front cover.

Because of the switch from NAD27 to NAD83, there are SPC27 and SPC83. Besides the change of the datum, SPC83 has a few other changes. SPC83 coordinates are published in meters instead of feet. The states of Montana, Nebraska, and South Carolina have each replaced multiple zones with a single SPC zone. California has reduced SPC zones from seven to six. And Michigan has changed from the transverse Mercator to the Lambert conformal conic projection. A list of SPC83 is available on the inside of this book's front cover.

Some states in the United States have developed their own statewide coordinate system. Montana, Nebraska, and South Carolina all have a single SPC zone, which can serve as the statewide coordinate system. Idaho is another example. Idaho is divided into two UTM zones (11 and 12) and three SPC zones (West, Central, and East). These zones work well as long as the study area is within a single zone. When a study area covers two or more zones, the data sets must be converted to a single zone for spatial registration. But the conversion to a single zone also means that the data sets can no longer maintain the accuracy level designed for the UTM or the SPC coordinate system. The Idaho statewide coordinate system, adopted in 1994 and modified in 2003, is still based on a transverse Mercator projection but its central meridian passes through the center of the state (114° W). (A complete list of parameters of the Idaho statewide coordinate system is included in Task 1 of the applications section.) Changing the location of the central meridian results in one zone for the entire state.

2.4.4 The Public Land Survey System

The **PLSS** is a land partitioning system (Figure 2.15). Using the intersecting township and range lines, the system divides the lands mainly in the central and western states into 6×6 mile squares or townships. Each township is further partitioned into 36 square-mile parcels of 640 acres, called sections.

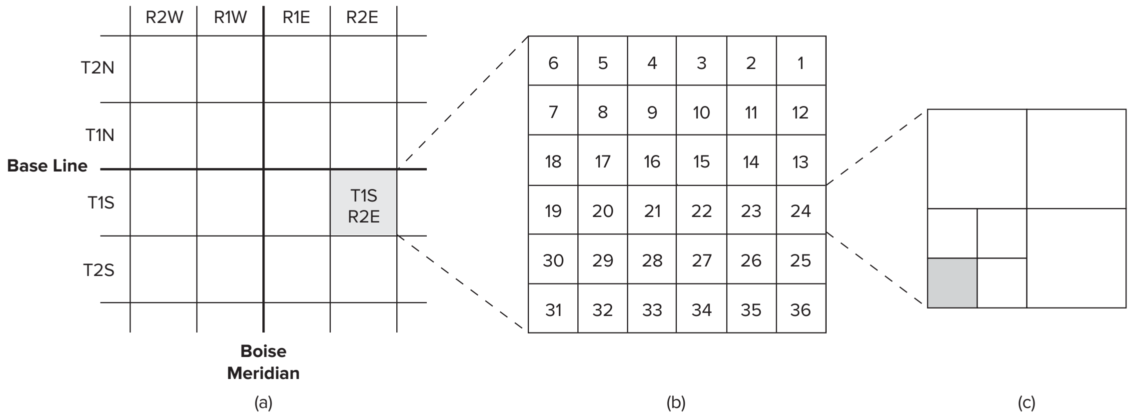

Figure 2.15
The shaded survey township in (a) has the designation of T1S, R2E. T1S means that the survey township is south of the base line by one unit. R2E means that the survey township is east of the Boise (principal) meridian by two units. Each survey township is divided into 36 sections in (b). Each section measures 1 mile × 1 mile or 640 acres and has a numeric designation. The shaded square in (c) measures 40 acres and has a legal description of the SW 1/4 of the SW 1/4 of Section 5, T1S, R2E.

(In reality, many sections are not exactly 1 mile by 1 mile in size.)

Land parcel layers are typically based on the PLSS. The U.S. Bureau of Land Management (BLM) has been working on a **Geographic Coordinate Data Base (GCDB)** of the PLSS for the western United States **(http://www.blm.gov/wo/st/en/prog/more/gcdb.html).** Generated from BLM survey records, the GCDB contains coordinates and other descriptive information for section corners and monuments recorded in the PLSS. Legal descriptions of a parcel layer can then be entered using, for example, bearing and distance readings originating from section corners.

2.5 Options for Coordinate Systems in GIS

Basic GIS tasks with coordinate systems involve defining a coordinate system, projecting geographic coordinates to projected coordinates, and reprojecting projected coordinates from one system to another.

A GIS package typically has many options of datums, ellipsoids, and coordinate systems. A constant challenge for GIS users is how to work with this large number of coordinate systems. GIS packages can offer assistance in the following three areas: projection file, predefined coordinate systems, and on-the-fly projection.

2.5.1 Projection File

A projection file is a text file that stores information on the coordinate system on which a data set is based. Box 2.4, for example, shows a projection file for the NAD 1983 UTM Zone 11N coordinate system. The projection file contains information on the geographic coordinate system, the map projection parameters, and the linear unit.

Besides identifying a data set's coordinate system, a projection file serves at least two other purposes: it can be used as an input for projecting or reprojecting the data set, and it can be exported to other data sets that are based on the same coordinate system.

2.5.2 Predefined Coordinate Systems

A GIS package typically groups coordinate systems into predefined and custom (Table 2.1).

Box 2.4 A Projection File Example

The following projection file example is used by ArcGIS to store information on the NAD 1983 UTM Zone 11N coordinate system:

PROJCS [“NAD_1983_UTM_Zone_11N”, GEOGCS[“GCS_North_American_1983”,
DATUM[“D_North_American_1983”,SPHEROID[“GRS_1980”,6378137.0,298.257222101]],
PRIMEM[“Greenwich”,0.0], UNIT[“Degree”,0.0174532925199433]],
PROJECTION [“Transverse_Mercator”], PARAMETER[“False_Easting”,500000.0],
PARAMETER[“False_Northing”,0.0], PARAMETER[“Central_Meridian”,–117.0],
PARAMETER[“Scale_Factor”,0.9996], PARAMETER[“Latitude_Of_Origin”,0.0],
UNIT[“Meter”,1.0]]

The information comes in three parts. The first part defines the geographic coordinate system: NAD83 for the datum, GRS80 for the spheroid, the prime meridian of 0° at Greenwich, and units of degrees. The file also lists the major axis (6378137.0) and the denominator of the flattening (298.257222101) for the spheroid. The number of 0.0174532925199433 is the conversion factor from degree to radian (an angular unit typically used in computer programming). The second part defines the map projection parameters of name, false easting, false northing, central meridian, scale factor, and latitude of origin. And the third part defines the linear unit in meters.

TABLE 2.1 A Classification of Coordinate Systems in GIS Packages

	Predefined	Custom
Geographic	NAD27, NAD83	Undefined local datum
Projected	UTM, State Plane	IDTM

A predefined coordinate system, either geographic or projected, means that its parameter values are known and are already coded in the GIS package. The user can therefore select a predefined coordinate system without defining its parameters. Examples of predefined coordinate systems include NAD27 (based on Clarke 1866) and Minnesota SPC83, North (based on a Lambert conformal conic projection and NAD83). In contrast, a custom coordinate system requires its parameter values to be specified by the user. The Idaho statewide coordinate system (IDTM) is an example of a custom coordinate system.

2.5.3 On-the-Fly Projection

On-the-fly projection is designed for displaying data sets that are based on different coordinate systems. The software package uses the projection files available and automatically converts the data sets to a common coordinate system on a temporary basis. This common coordinate system is by default the coordinate system of the first layer in display, or it can be defined by the user for a group of layers.

On-the-fly projection does not actually change the coordinate system of a data set. Thus, it cannot replace the task of projecting and reprojecting data sets in a GIS project. If a data set is to be used frequently in a different coordinate system, we should reproject the data set. And if the data