GIS Fundamentals:

A First Text on Geographic Information Systems

6th Edition

Paul Bolstad

University of Minnesota - Twin Cities

XanEdu

Errata and other helpful information about this book may be found at http://www.paulbolstad.net/gisbook.html

GIS Fundamentals: A first text on geographic information systems, 6th edition.

Cover image courtesy NASA, from the ASTER instrument, Terra Satellite, of the Ubinas volcano, April, 2014.

First printing June, 2019
Eider Press, 2303 4th St. White Bear Lake, MN 55110

Book available from XanEdu in both print and electronic formats, inquiries at http://www.xanedu.com/contact/

Instructor resources available at www.paulbolstad.net, or at www.paulbolstad.org

ISBN 978-1-59399-552-2

XanEdu

4750 Venture Drive, Suite 400
Ann Arbor, MI 48108
800-562-2147
www.xanedu.com

Output: Hardcopy Maps, Digital Data, and Metadata

We create spatial data to use, share, and archive. Maps are often produced during data creation and distribution, as intermediate documents while editing, for analysis, or as finished products to communicate some aspect of our data. To be widely useful, we must also generate information, or "metadata," about the spatial data we've created, and we may have to convert our data to standard forms. This section describes some characteristics of data output. We start with a brief treatment of cartography and map design, by which we produce hardcopy and digital maps. We then provide a description of metadata, and some observations on data conversion and data transfer standards.

Cartography and Map Design

Cartography is the art and techniques of making maps. It encompasses both mapmaking tools and how these tools may be combined to communicate spatial information. Cartography is a discipline of much depth and breadth, and there are many books, journal articles, conferences, and societies devoted to the science and art of cartography. Our aim in the next few pages is to provide a brief overview of cartography with a particular focus on map design. This is both to acquaint new students with the most basic concepts of cartography, and help them apply these concepts in the consumption and production of spatial information. Readers interested in a more complete treatment should consult the references listed at the end of this chapter.

A primary purpose of cartography is to communicate spatial information. This requires identification of the

-intended audience,

-information to communicate,

-area of interest,

-physical and resource limitations;

in short, the whom, what, where, and how we may present our information.

These considerations drive the major cartographic design decisions we make each time we produce a map. We must consider the:

-scale, size, shape, and other general map properties,

-data to plot,

-symbol shapes, sizes, or patterns,

-labeling, including font type and size,

-legend properties, size, and borders, and

-the placement of all these elements on a map.

Map scale, size, and shape depend primarily on the intended map use. Wall maps for viewing at a distance of a meter or more may have few, large, boldly colored features. In contrast, commonly produced street maps for navigation in metropolitan areas are detailed, to be viewed at short ranges, and have a rich set of additional tables, lists, or other features.

Map scale is often determined in part by the size of the primary objects we wish to display, and in part by the most appropriate media sizes, such as the page or screen size possible for a document. As noted earlier, the map scale is the ratio of lengths on a map to true lengths. If we wish to display an area that spans 25 km (25,000 m) on a screen that spans 25 cm (0.25 m), the map scale will be near 0.25 to 25,000, or 1:100,000. This decision on size, area, and scale then drives further map design. For example, scale limits the features we may display, and the size, number, and labeling of features. At a 1:100,000 scale we may not be able to show all cities, burgs, and towns, as there may be too many to fit at a readable size.

Maps typically have a primary theme or purpose that is determined by the intended audience. Is the map for a general population, or for a target audience with specific expectations for map features and design? General purpose maps typically have a wide range of features represented, including transportation networks, towns, elevation, or other common features (Figure 4-32a). Special purpose maps, such as road maps, focus on a more limited set of features, in this instance road locations and names, town names, and large geographic features (Figure 4-32b).

Once the features to include on a map are defined, we must choose the symbols used to draw them. Symbology depends in part on the type of feature. For example, we have a different set of options when representing continuous features such as elevation or pollution concentration than when representing discrete features. We also must choose among symbols for each of the types of discrete features; for example, the set of symbols for points are generally different from those for line or area features.

Symbol size is an important attribute of map symbology, often specified in a unit called a *point*. One point is approximately equal to 0.467 mm, or about 1/55th of an inch. A specific point number is most often used to specify the size of symbols, for example, the dimensions of small squares to represent houses on a map, or the characteristics of a specific pattern used to fill areas on a map. A line width may also be specified in points. Setting a line width of two points means we want that particular line plotted with a width of 0.93 mm. It is unfortunate that “point” is both the name of the distance unit and a general property of a geographic feature, as in “a tree is a point feature.” This forces us to talk about the “point size” of symbols to represent points, lines, or area fills or patterns, but if we are careful, we may communicate these specifications clearly.

The best size, pattern, shape, and color used to symbolize each feature depends on the viewing distance; the number, density, and type of features; and the purpose of the map. Generally, we use larger, bolder, or

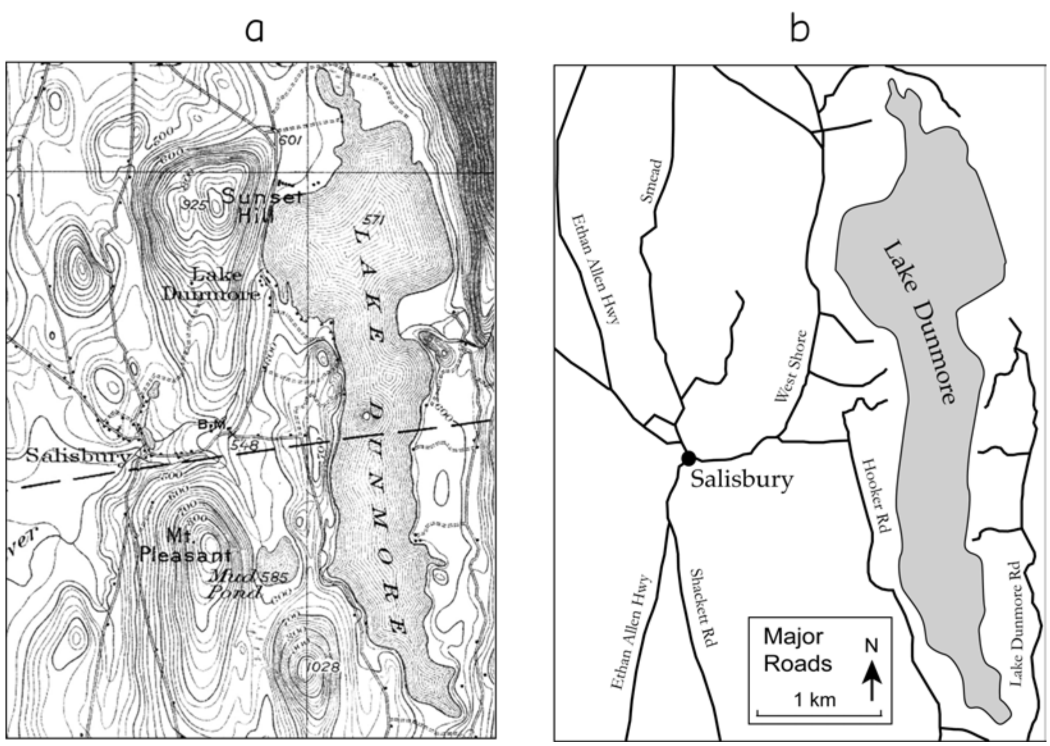

Figure 4-32: Example of a) a detailed, general-purpose map, here a portion of a United States Geological Survey map, and b) a specialized map focusing on a specific set of selected features, here showing roads. The features chosen for depiction on the map depend on the intended map use.

thicker symbols for maps to be viewed from longer distances, while we reduce this limit when producing maps for viewing at 50 cm (20 in). Most people with normal vision under good lighting may resolve lines down to near 0.2 points at close distances, provided the lines show good contrast with the background. Although size limits depend largely on background color and contrast, point features are typically not resolvable at sizes smaller than about 0.5 points, and distinguishing between shapes is difficult for point features smaller than approximately 2 points in their largest dimension.

The pattern and color of symbols must also be chosen, generally from a set provided by the software (Figure 4-33). Symbols generally distinguish among feature type by characteristics, and although most symbols are not associated with a feature type, some are, such as, plane outlines for airports, numbered shields for highways, or a hatched line for a railroad.

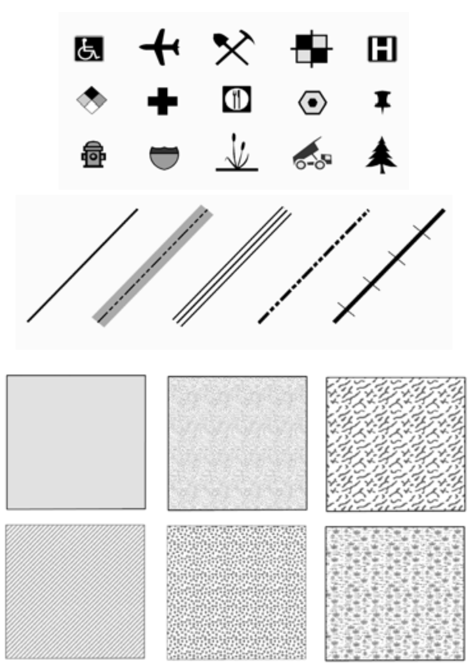

Figure 4-33: Examples of point (top), line (mid), and area (bottom) symbols used to distinguish among features of different types. Most GIS software provides a set of standard symbols for point, line, area, and continuous surface features.

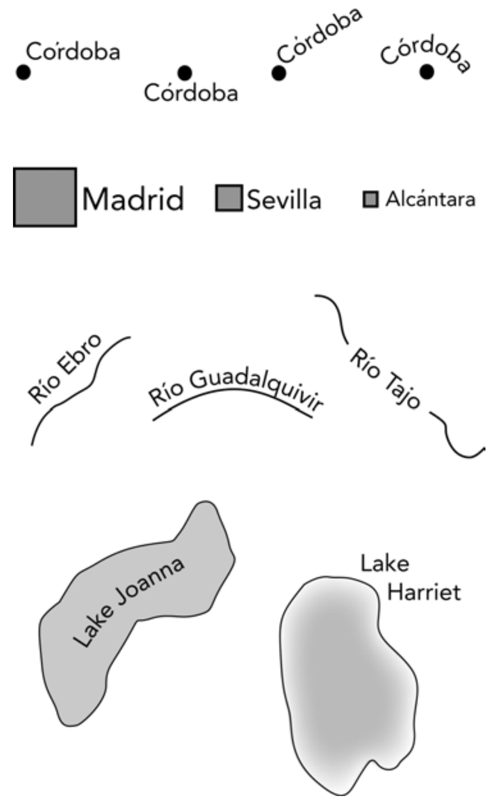

Figure 4-34: Common labeling options, including straight, angled, wrapped text, and graduated labels for points (top two sets), and angled, wrapped, fronting, and embedded labels for line and polygon features (bottom two sets).

We also must often choose whether and how to label features. Most GIS software provides a range of tools for creating and placing labels, and in all cases we must choose the label font type and size, location relative to the feature, and orientation. Primary considerations when labeling point features are label placement relative to the point location, label size, and label orientation (Figure 4-34). We may also use graduated labels, that is, resize them according to some variable associated with the point feature. For example, it is common to have larger features and label fonts for larger cities (Figure 4-34). Labels may be bent, angled, or wrapped around features to improve clarity and more efficiently use space in a map.

Label placement is very much an art, and there is often much individual editing required when placing and sizing labels for finished maps. Most software provides for automatic label placement, usually specified relative to feature location. For example, one may specify labels above and to the right of all points, or line labels placed over line features, or polygon labels placed near the polygon centroid. However, these automatic placements may not be satisfactory because labels may overlap, labels may fall in cluttered areas of the map, or features associated with labels may be ambiguous. Some software provides options for automatic label placement, including removal or movement of overlapping labels. These often reduce manual editing, but sometimes increase it.

Figure 4-35 shows a portion of a map of southern Finland. This region presents several mapping problems, including the high density of cities near the upper right, an irregular coastline, and dense clustering of islands along the coast. Most labels are

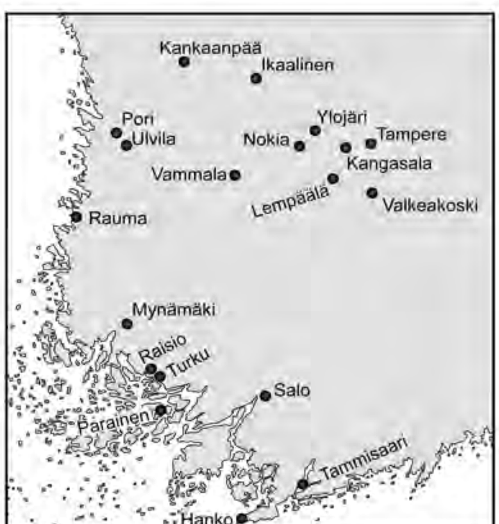

Figure 4-35: Example label placement for cities in southern Finland.

placed above and to the right of their corresponding city; however, some are moved or angled for clarity. Cities near the coast show both, to avoid labels crossing the water/land boundary where practical. Semitransparent background shading is added for Parainen and Hanko, cities placed in the island matrix. This example demonstrates the individual editing often required when placing labels.

Most maps should have legends. The legend identifies map features succinctly and describes the symbols used to depict those features. Legends often include or are grouped with additional map information such as scale bars, north arrows, and descriptive text. The cartographer must choose the size and shape of the descriptive symbol, and the font type, size, and orientation for each symbol in the legend. The primary goal is to have a clear, concise, and complete legend.

The kind of symbols appropriate for map legends depends on the types of features depicted. Different choices are available for point, line, and polygon features, or for continuously variable features stored as rasters. Most software provides a range of legend elements and symbols that may be used. Typically, these tools allow a wide range of symbolizations, and a compact way of describing the symbolization in a legend (Figure 4-36).

The specific layout of legend features must be defined; for example, the point feature symbol size may be graduated based on some attribute for the points. Successively larger features may be assigned for successively larger cities. This must be noted in the legend, and the symbols nested, shown sequentially, or otherwise depicted (Figure 4-36, top left).

The legend should be exhaustive. Examples of each different symbol type that appears on the map should appear in the legend. This means each point, line, or area symbol is drawn in the legend with some descriptive label. Labels may be next to, wrapped around, or embedded within the features, and sometimes descriptive numbers are added, for example, a range of continuous variables (Figure 4-36, upper left). Scale bars, north arrows, and descriptive text boxes are typically included in the legend.

Map composition or layout is another primary task. Composition consists of determining the map elements, their size, and their placement. Typical map elements, shown in Figure 4-3 and Figure 4-4, include one or more main data panes or areas, a legend, a title, a scale bar and north arrow, a grid or graticule, and perhaps descriptive text. These each must be sized and placed on the map.

These map elements should be positioned and sized in accordance with their importance. The map's most important data pane should be largest, and it is often centered or otherwise given visual dominance. Other elements are typically smaller and located around the periphery or embedded within the main data pane. These other elements include map insets, which are smaller data panes that show larger or smaller scale views of a region in the primary data pane. Good map compositions usually group related elements and use empty space effectively. Data panes are often grouped and legend elements placed near each other, and grouping is often indicated with enclosing boxes.

Neophyte cartographers should avoid two tendencies in map composition, both depicted in Figure 4-37. First, it is generally easy to create a map with automatic label and legend generation and placement. The map shown at the top of Figure 4-37 is typical of this automatic composition, and includes poorly placed legend elements and too small, poorly placed labels. Labels crowd each other, are ambiguous, and cross water/land or other feature boundaries, and fonts are poorly chosen. You should note that automatic map symbol selection and placement is nearly always suboptimal, and the novice cartographer should scrutinize these choices and manually improve them.

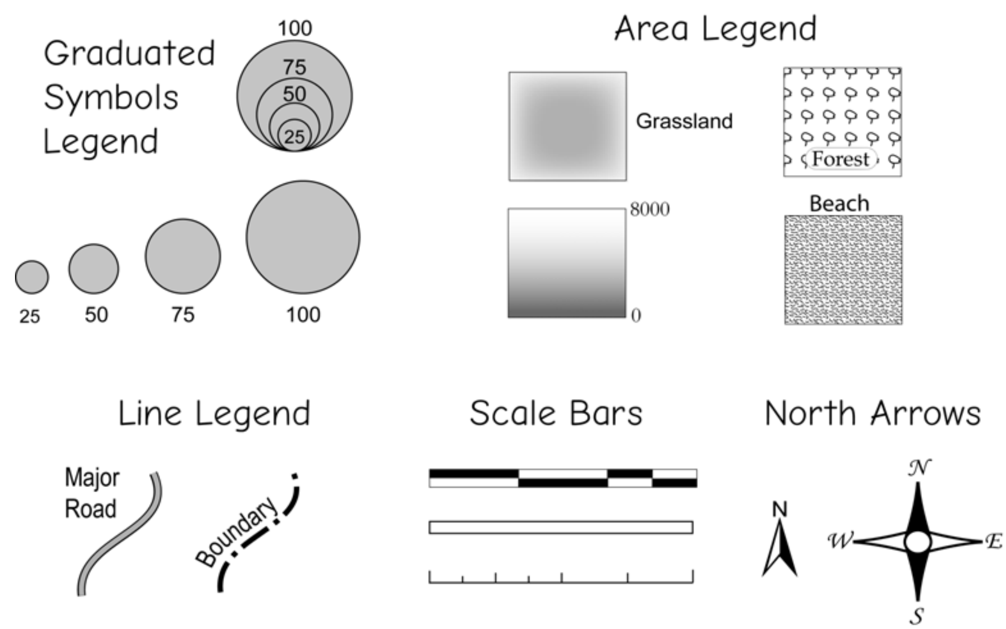

Figure 4-36: Examples of legend elements and representation of symbols. Some symbols may be grouped in a compact way to communicate the values associated with each symbol, e.g., sequential or nested graduated circles to represent city population size, area pattern or color fills to distinguish among different polygon features, line and point symbols, and informative elements such as scale bars and north arrows.

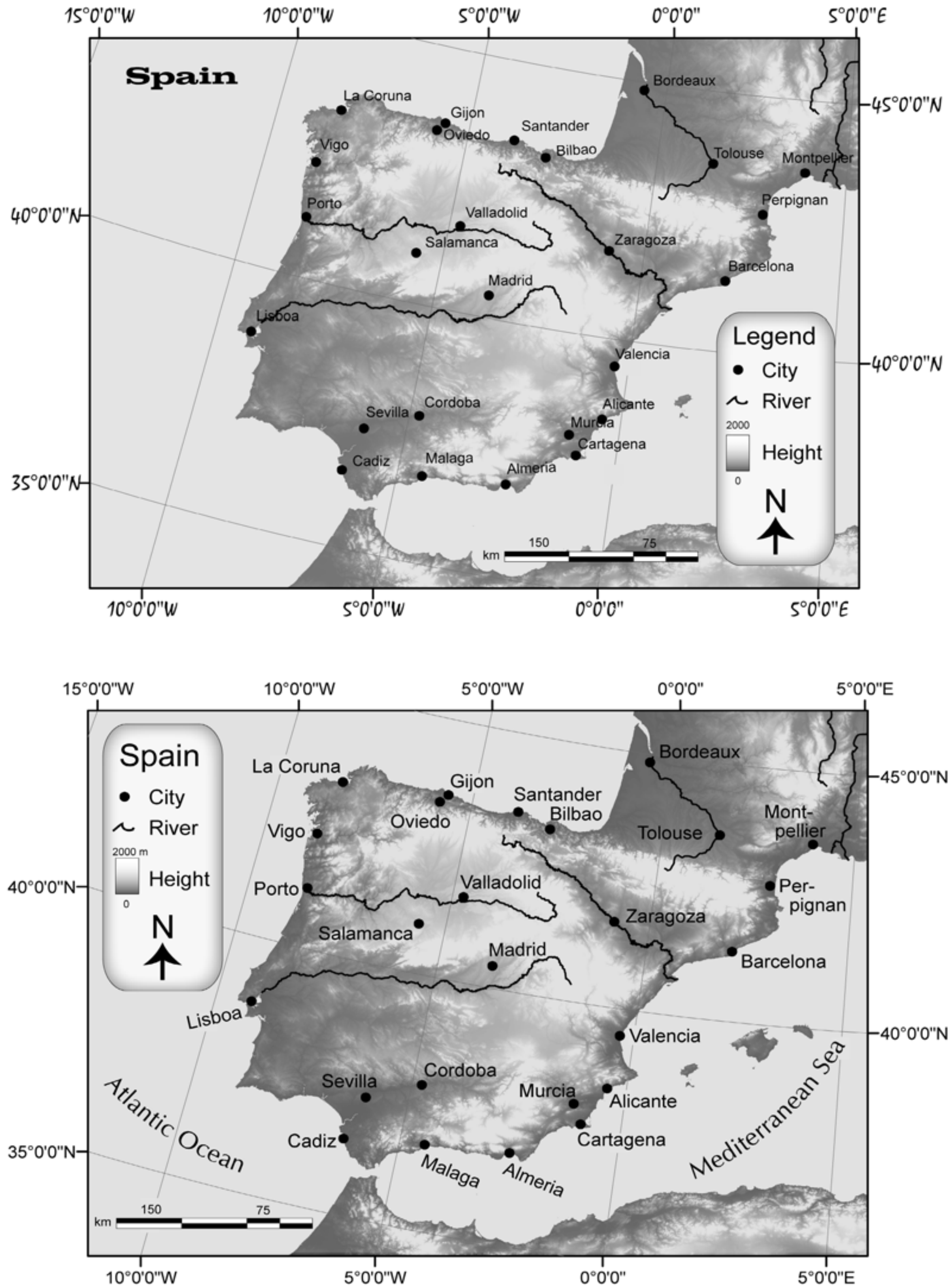

Figure 4-37: An example of poor map design (top). This top panel shows a number of mistakes common for the neophyte cartographer, including small labels (cities) and mismatched fonts (graticule labels, title), poor labeling (city labels overlapping, ambiguously placed, and crossing distinctly shaded areas), unlabeled features (oceans and seas), poorly placed scale bar and legend, and unbalanced open space on the left side of the map. These problems are not present in the improved map design, shown in the lower panel.

The second common error is poor use of empty space, those parts of the map without map elements. There are two opposite tendencies: either to leave too much or unbalanced empty space or to clutter the map in an attempt to fill all empty space. Note that the map shown at the top of Figure 4-37 leaves large empty spaces on the left (western) edge, with the Atlantic Ocean devoid of features. The cartographer may address this in several ways: by changing the size, shape, or extent of the area mapped; by adding new features, such as data panes as insets, additional text boxes, or other elements; or by moving the legend or other map elements to that space. The map shown at the bottom of Figure 4-37, while not perfect, fixes these design flaws, in part by moving the legend and scale bar, and in part by adding labels for the Atlantic Ocean and Mediterranean Sea. The empty space is more balanced in that it appears around the major map elements in approximately equal proportions.

As noted earlier, this is only a brief introduction to cartography, a subject covered by many good books, some listed at the end of this chapter. Perhaps the best compendium of examples is the Map Book Series, by ESRI, published annually since 1984. Examples are available at the time of this writing at www.esri.com/mapmuseum. You should leaf through several volumes in this series, with an eye toward critical map design. Each volume contains many beautiful and informative maps, and provides techniques worth emulating.

Digital Data Output

We often must transfer digital data we create to another user, or use data developed by others. Given the number of different GIS software, operating systems, and computer types, transferring data is not always a straightforward process. Digital data output typically includes two components, the data themselves in some standard, defined format, and *metadata*, or data about the digital data. We will describe data formats and metadata in turn.

Digital data are the data in some electronic form. As described at the end of the first chapter, there are many file formats, or ways of encoding the spatial and attribute data in digital files. Digital data output often consists of recording or converting data into one of these file formats. These data are typically converted with a utility, tool, or option available in the data development software (Figure 4-38). The most useful of these utilities supports a broad range of input and output options, each fully described in the program documentation.

All formats strive for complete data transfer without loss. They must transmit the spatial and attribute data, the metadata, and all other information necessary to effectively use the spatial data. There are many digital data output formats, although many are legacy formats that are used with decreasing frequency.

A common contemporary format is the *Geographic Markup Language (GML)*. This is an extension of XML for geographic features; XML is in turn the lingua franca for human/machine readable documents. As with most XML, there are two parts for any

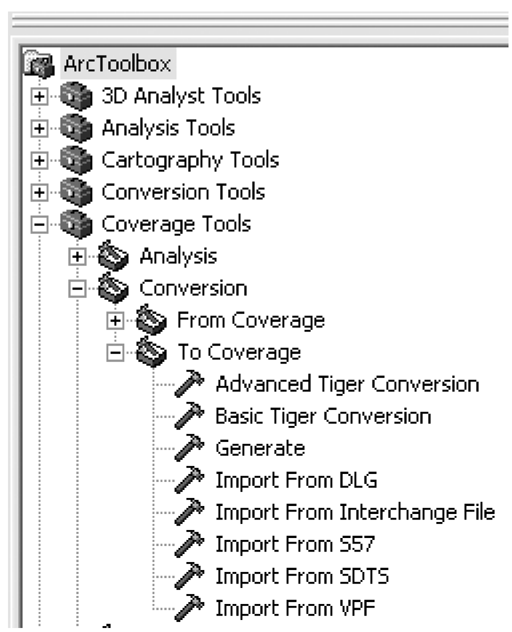

Figure 4-38: An example of a conversion utility, here from the ESRI ArcGIS software. Date may be converted from one of several formats to an ESRI-specific digital data.

GML dataset: a schema that describes the document, and the document containing the geographic data. GML is a standard, but there can be many extensions, so a community of users can extend the standard with additional features, and document the extension in a standard way.

There are many legacy digital data transfer formats that were widely used before GML. GML replaced a withdrawn standard, the *Spatial Data Transfer Standard* (SDTS), with translators available to or from this older format. There are several U.S. Geological Survey formats for the transfer of digital elevation models or digital vector data, or software-specific formats, such as an ASCII format (GEN/UNGEN) that was developed by ESRI. These were useful for a limited set of transfers, but shortcomings in each of these transfer formats led to the development of subsequent standards. These formats are not common, but sometimes arise in converting older data sets.

Metadata: Data Documentation

Metadata are information about spatial data. Metadata describe the content, source, lineage, methods, developer, coordinate system, extent, structure, spatial accuracy, attributes, and responsible organization for spatial data.

Metadata are required for the effective use of spatial data. Metadata allow the efficient transfer of information about data, and inform new users about the geographic extent, coordinate system, quality, and other data characteristics. Metadata aid organizations in evaluating data to determine if they are suitable for an intended use, e.g., to review accuracy, coverage, or information needs. Metadata may also aid in data updates by guiding the choice of appropriate collection methods and formats for new data.

Most governments have or are in the process of establishing standard methods for reporting metadata. In the United States, the Federal Geographic Data Committee (FGDC) has defined a Content Standard for Digital Geospatial Metadata (CSDGM) to specify the content and format for metadata. The CSDGM ensures that spatial data are clearly described so that they may be used effectively within an organization. The use of the CSDGM also ensures that data may be described to other organizations in a standard manner, and that spatial data may be more easily evaluated by and transferred to other organizations.

The CSDGM consists of a standard set of elements that are presented in a specified order. The standard is exhaustive in the information it provides, and is flexible in that it may be extended to include new elements for new categories of information in the future. There are over 330 different elements in the CSDGM. Some of these elements contain information about the spatial data, and some elements describe or provide linkages to other elements. Elements have standardized long and short names and are provided in a standard order with a hierarchical numbering system. For example, the westernmost bounding coordinate of a data set is element 1.5.1.1, defined as follows:

1.5.1.1 West Bounding Coordinate – westernmost coordinate of the limit of coverage expressed in longitude.

Type: real

Domain: -180.0 < = West Bounding Coordinate < 180.0

Short Name: westbc

The numbering system is hierarchical. Here, 1 indicates it is basic identification information, 1.5 indicates identification information about the spatial domain, 1.5.1 is for bounding coordinates, and 1.5.1.1 is the western most bounding coordinate.

There are 10 basic types of information in the CSDGM:

1) identification, describing the data set,

2) data quality,

3) spatial data organization,

4) spatial reference coordinate system,

5) entity and attribute,

6) distribution and options for obtaining the data set,

7) currency of metadata and responsible party,

8) citation,

9) time period information, used with other sections to provide temporal information, and

10) contact organization or person.

The CSDGM is a content standard and does not specify the format of the metadata. As long as the elements are included, properly numbered, and identified with correct values describing the data set, the metadata are considered to conform with the CSDGM. Indentation and spacing are not specified. However, because metadata may be quite complex, there are a number of conventions that are emerging in the presentation of metadata. These conventions seek to ensure that metadata are presented in a clear, logical way to humans, and are also easily ingested by computer software. There is a Standard Generalized Markup Language (SGML) for the exchange of metadata. An example of a portion of the metadata for a 1:100,000 scale digital line graph data set is shown in Figure 4-39.

Metadata are most often created using specialized software tools. Although meta-

```
4. Spatial_Reference_Information:
  4.1 Horizontal_Coordinate_System_Definition:
    4.1.2 Planar:
      4.1.2.2 Grid_Coordinate_System:
        4.1.2.2.1 Grid_Coordinate_System_Name:
                         Universal Transverse Mercator
        4.1.2.2.2 Universal_Transverse_Mercator:
          4.1.2.2.2.1 UTM_Zone_Number: 10-19
      4.1.2.4 Planar_Coordinate_Information:
        4.1.2.4.1 Planar_Coordinate_Encoding_Method:
                                    coordinate pair
        4.1.2.4.2 Coordinate_Representation:
          4.1.2.4.2.1 Abscissa_Resolution: 2.54
          4.1.2.4.2.2 Ordinate_Resolution: 2.54
        4.1.2.4.4 Planar_Distance_Units: meters
    4.1.4 Geodetic_Model:
      4.1.4.1 Horizontal_Datum_Name: North American Datum 1927
      4.1.4.2 Ellipsoid_Name: Clark 1866
      4.1.4.3 Semi-major_Axis: 6378206.4
      4.1.4.4 Denominator_of_Flattening_Ratio: 294.98
  4.2 Vertical_Coordinate_System_Definition:
    4.2.1 Altitude_System_Definition:
      4.2.1.1 Altitude_Datum_Name:
                  National Geodetic Vertical Datum of 1929
      4.2.1.2 Altitude_Resolution: 1
      4.2.1.3 Altitude_Distance_Units: feet or meters
      4.2.1.4 Altitude_Encoding_Method: attribute values
    4.2.2 Depth_System_Definition:
      4.2.2.1 Depth_Datum_Name: Mean lower low water
      4.2.2.2 Depth_Resolution: 1
      4.2.2.3 Depth_Distance_Units: meters or feet
      4.2.2.4 Depth_Encoding_Method: attribute values
```

Figure 4-39: Example of a small portion of the FGDC recommended metadata for a 1:100,000 scale derived digital data set.

data may be produced using a text editor, the numbering system, names, and other conventions are laborious to type. There are often complex linkages between metadata elements, and some elements are repeated or redundant. Software tools may ease the task of metadata entry by reducing redundant entries, ensuring correct linkages, and checking elements for contradictory information or errors. For example, the metadata entry tool may check to make sure the westernmost boundary is west of the easternmost boundary. Metadata are most easily and effectively produced when their development is integrated into the workflow of data production.

Although not all organizations in the United States adhere to the CSDGM metadata standard, most organizations record and organize a description and other important information about their data, and many organizations consider a data set incomplete if it lacks metadata. All U.S. government units are required to adhere to the CSDGM when documenting and distributing spatial data.

Many other national governments are developing metadata standards. One example is the spatial metadata standard developed by the Australia and New Zealand Land Information Council (ANZLIC), known as the ANZLIC Metadata Guidelines. ANZLIC is a group of government, business, and academic representatives working to develop spatial data standards. The ANZLIC metadata guidelines define the core elements of metadata, and describe how to write, store, and disseminate these core elements. Data entry tools, examples, and spatial data directory have been developed to assist in the use of ANZLIC spatial metadata guidelines.

There is a parallel effort to develop and maintain international standards for metadata. The standards are known as the ISO 19115 International Standards for Metadata. According to the International Standards Organization, the ISO 19115 "defines the schema required for describing geographic information and services. It provides information about the identification, the extent, the quality, the spatial and temporal schema, spatial reference, and distribution of digital geographic data."

There is a need to reconcile international and national metadata standards, because they may differ. National standards may require information not contained in international standards, or vice versa. Governments typically create *metadata profiles* that are consistent with the international standard. These profiles establish the correspondence between elements in the different standards, and identify elements of the international profile that are not in the national profile.

Summary

Spatial data entry is a common activity for many GIS users. Although data may be derived from several sources, maps are a common source, and care must be taken to choose appropriate map types and to interpret the maps correctly when converting them to spatial data in a GIS.

Maps are used for spatial data entry due to several unique characteristics. These include our long history of hardcopy map production, so centuries of spatial information are stored there. In addition, maps are inexpensive, widely available, and easy to convert to digital forms, although the process is often time consuming, and may be costly. Maps are usually converted to digital data through a manual digitization process, whereby a human analyst traces and records the location of important features. Maps may also be digitized via a scanning device.

The quality of data derived from a map depends on the type and size of the map, how the map was produced, the map scale, and the methods used for digitizing. Large-scale maps generally provide more accurate positional data than comparable small-scale maps. Large-scale maps often have less map generalization, and small horizontal errors in plotting, printing, and digitizing are magnified less during conversion of large-scale maps.

Snapping, smoothing, vertex thinning, and other tools may be used to improve the quality and utility of digitized data. These methods are used to ensure positional data are captured efficiently and at the proper level of detail.

Map and other data often need to be converted to a target coordinate system via a map transformation. Transformations are different from map projections (discussed in Chapter 3), in that a transformation uses an empirical, least squares process to convert coordinates from one Cartesian system to another. Transformations are often used when registering digitized data to a known coordinate system. Map transformations should not be used when a map projection is called for.

Cartography is an important aspect of GIS, because we often communicate spatial information through maps. Map design depends on both the target audience and purpose, setting and modes of map viewing, and available resources. Proper map design considers the scale, symbols, labels, legend, and placement to effectively communicate the desired information.

Metadata are the "data about data." They describe the content, origin, form, coordinate system, spatial and attribute data characteristics, and other relevant information about spatial data. Metadata facilitate the proper use, maintenance, and transfer of spatial data. Metadata standards have been developed, both nationally and internationally, with profiles used to cross-reference elements between metadata standards. Metadata are a key component of spatial data, and many organizations do not consider data complete until metadata have been created.

Suggested Reading

Aronoff, S. (1989). *Geographic Information Systems, A Management Perspective*. Ottawa: WDL Publications.

Bolstad, P., Gessler, P., Lillesand, T.M. (1990). Positional uncertainty in manually digitized map data. *International Journal of Geographical Information Systems*, 4:399–412.

Burrough, P.A., Frank, A.U. (1996). *Geographical Objects with Indeterminate Boundaries*. London: Taylor & Francis.

Chrisman, N.R. (1984). The role of quality information in the long-term functioning of a geographic information system. *Cartographica*, 21:79-87.

Chrisman, N.R. (1987). Efficient digitizing through the combination of appropriate hardware and software for error detection and editing. *International Journal of Geographical Information Systems*, 1:265–277.

DeMers, M. (2000). *Fundamentals of Geographic Information Systems* (2nd ed.). New York: Wiley.

Douglas, D.H., Peuker, T.K. (1973). Algorithms for the reduction of the number of points required to represent a digitized line or its caricature. *Canadian Cartographer*, 10:112–122.

Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., Tyler C. (2002). The National Elevation Dataset. *Photogrammetric Engineering and Remote Sensing*, 68:5–32.

Holroyd, F., Bell, S.B.M. (1992). Raster GIS: Models of raster encoding. *Computers and Geosciences*, 18:419–426.

Joao, E.M. (1998). *Causes and Consequences of Map Generalization.* London: Taylor & Francis.

Laurini, R., Thompson, D. (1992). *Fundamentals of Spatial Information Systems*. London: Academic Press.

Maquire, D.J., Goodchild, M.F., Rhind, D. (Eds.). (1991). *Geographical Information Systems: Principles and Applications*. Harlow: Longman Scientific.

McBratney, A.B., Santos, M.L.M., Minasny, B. (2003). On digital soil mapping. *Geoderma,* 117:3–52.

Muehrcke, P.C., Muehrcke, J.P. (1992). *Map Use: Reading, Analysis, and Interpretation* (3rd ed.). Madison: J.P. Publications.

Nagy, G., Wagle, S.G. (1979). Approximation of polygonal maps by cellular maps. *Communications of the Association of Computational Machinery*, 22:518–525.

Peuker, T.K., Chrisman, N. (1975). Cartographic data structures. *The American Cartographer*, 2:55–69.

Peuquet, D.J. (1984). A conceptual framework and comparison of spatial data models. *Cartographica*, 21:66–113.

Peuquet, D.J. (1981). An examination of techniques for reformatting digital cartographic data. Part II: the raster to vector process. *Cartographica*, 18:21–33.

Shaeffer, C.A., Samet, H., Nelson, R.C. (1990). QUILT: a geographic information system based on quadtrees. *International Journal of Geographical Information Systems*, 4:103–132.

Shea, K.S., McMaster, R.B. (1989). Cartographic generalization in a digital environment: when and how to generalize. *Proceedings AutoCarto 9*, 56–67.

Warner, W., Carson, W. (1991). Errors associated with a standard digitizing tablet. *ITC Journal*, 2:82–85.

Weibel, R. (1997). Generalization of spatial data: principles and selected algorithms. In van Kreveld, M., Nievergelt, J., Roos, T., Widmayer, P., (Eds.). *Algorithmic Foundations of Geographic Information Systems*. Berlin: Springer-Verlag.

Wolf, P.R., Ghilani, C. (2002). *Elementary Surveying, an Introduction to Geomatics* (10th ed.). New Jersey: Prentice-Hall.

Zeiler, M. (1999). *Modeling Our World: The ESRI Guide to Geodatabase Design*. Redlands: ESRI Press.