6

Scale and Generalization

OVERVIEW

This chapter presents basic concepts in scale and generalization. Scale is a fundamental geographic principle, although there is often confusion about the exact meaning of ***geographic scale, cartographic scale****, and* ***data resolution****. Geographers think about scale as area covered, where large-scale studies cover a large region such as a state. Cartographers think about scale mathematically and use the standard* ***representative fraction (RF)*** *to express the relationship between map and Earth distance. For instance, most national map series are established at a specific scale, such as the French 1: 25,000 BD Topo, and the USGS's 1:24,000 series. Data resolution refers to the granularity of the data, such as the pixel size of a remote sensing image. Directly related to the concept of scale is the idea of generalization, and modifying the information content so that it is appropriate at a given scale. It would not be possible, for instance, to depict the street network for the entire United States with the country mapped at a scale that would fit one page—only major highways could be depicted.*

Section 6.1 introduces the concept of geographic and cartographic scale and covers how scale controls the amount of map space and thus the appropriate information content. The concepts of cartographic and geographic scale and representative fraction are explained. Section 6.2 provides some basic definitions of ***generalization****, including a discussion of some fundamental generalization operations. Section 6.3 discusses several conceptual models of the generalization process. One of the more complete models divides the process into why, when, and how components of generalization. Section 6.4 describes the many operations that have been designed for the generalization process and provides frameworks for their organization. In particular, extensive discussions of the* ***simplification*** *and* ***smoothing*** *operations are included. Section 6.5 illustrates a variety of generalization methods applied to several scales of a TIGER database for the Tampa-St. Petersburg area of Florida.*

6.1 GEOGRAPHIC AND CARTOGRAPHIC SCALE

Scale is a fundamental concept in all of science and is of particular concern to geographers, cartographers, and others interested in geospatial data. Astronomers work at a spatial scale of light years, physicists work at the atomic spatial scale in mapping the Brownian motion of atoms, and geographers work at spatial scales from the human to the global. Within the fields of geography and cartography, the terms **geographic scale** and **cartographic scale** are often confused. Geographers and other social scientists use the term scale to mean the extent of the study area, such as a neighborhood, city, region, or state. Here, large scale indicates a large area—such as a state—whereas small scale represents a smaller entity—such as a neighborhood. Climatologists, for instance, talk about large-scale global circulation in relation to the entire Earth; in contrast, urban geographers talk about small-scale gentrification of a part of a city. Alternatively, cartographic scale is based on a strict mathematical principle: the **representative fraction (RF)**. The RF, which expresses the relationship between map and Earth distances, has become the standard measure for map scale in cartography. The basic format of the RF is quite simple, where RF is expressed as a ratio of map units to earth units (with the map units standardized to 1). For example, an RF of 1:25,000 indicates that one unit on the map is equivalent to 25,000 units on the surface of the Earth. The elegance of the RF is that the measure is unitless—with our example the 1:25,000 could represent inches,

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feet, or meters. Of course, in the same way that ½ is a larger fraction than ¼, 1:25,000 is a larger scale than 1:50,000. Related to this concept, a scale of 1:25,000 depicts relatively little area but in much greater detail, whereas a scale of 1:250,000 depicts a larger area in less detail. Thus, it is the cartographic scale that determines the mapped space and level of geographic detail possible. It is important to realize that with cartographic scale the larger the representative fraction, the more detail (information content) is possible; the smaller the representative fraction, the less detail is possible. At the extreme, architects work at very large scales, perhaps 1:100, where individual rooms and furniture can be depicted, whereas a standard globe might be constructed at a scale of 1:30,000,000, allowing for only the most basic of geographic detail to be provided. As noted in Chapter 11, there are design issues that have to be considered when representing scales on maps, and a variety of methods for representing scale, including the RF, the verbal statement, and the graphical bar scale.

The term **data resolution**, which is related to scale, indicates the granularity of the data that is used in mapping. If mapping population characteristics of a city—an urban scale—the data can be acquired at a variety of resolutions, including census blocks, block groups, tracts, and even minor civil divisions (MCDs). Each level of resolution represents a different "grain" of the data. Likewise, when mapping biophysical data using remote sensing imagery, a variety of spatial resolutions are possible based on the sensor. Common grains are 79 meters (Landsat Multi-Spectral Scanner), 30 meters (Landsat Thematic Mapper), 20 meters (SPOT HRV multispectral), and 1 meter (Ikonos panchromatic). Low resolution refers to coarser grains (counties) and high resolution refers to finer grains (blocks). Cartographers must be careful to understand the relationship among geographic scale, cartographic scale, and data resolution, and how these influence the information content of the map.

6.1.1 Multiple-Scale Databases

Increasingly, cartographers and other geographic information scientists require the creation of multiscale/multiresolution databases from the same digital data set. This assumes that one can generate, from a master database, additional versions at a variety of scales. The need for such multiple-scale databases is a result of the requirements of the user. For instance, when mapping census data at the county level a user might wish to have significant detail in the boundaries. Alternatively, when using the same boundary files at the state level, less detail is needed. Because the generation of digital spatial data is extremely expensive and time-consuming, one master version of the database is often created and smaller scale versions are generated from this master scale. Further details are provided later.

6.2 DEFINITIONS OF GENERALIZATION

6.2.1 Definitions of Generalization in the Manual Domain

Generalization is the process of reducing the information content of maps due to scale change, map purpose, intended audience, and/or technical constraints. For instance, when reducing a 1:24,000 topographic map (large scale) to 1:250,000 (small scale), some of the geographical features must be either eliminated or modified because the amount of map space is significantly reduced. Of course, all maps are to some degree generalizations, as it is impossible to represent all features from the real world on a map, no matter what the scale. A quote from Lewis Carroll's (1893) *Sylvie and Bruno Concluded* nicely illustrates this concept:

> "That's another thing we've learned from your Nation," said Mein Herr, "map making." "But we've carried it much further than you. What do you consider the largest map that would be really useful?"
>
> "About six inches to the mile."
>
> "Only about six inches!" exclaimed Mein Herr. "We very soon got to six yards to the mile. Then we tried a hundred yards to the mile. And then came the grandest idea of all! We actually made a map of the country on a scale of a mile to the mile!"
>
> "Have you used it much?" I enquired.
>
> "It has never been spread out yet," said Mein Herr. "The farmers objected: they said it would cover the whole country, and shut out the sunlight! So now we use the country itself, as its own map, and I assure you it does nearly as well."

Cartographers have written on the topic of cartographic generalization since the early part of the 20th century. Max Eckert, the seminal German cartographer and author of *Die Kartenwissenschaft*, wrote in 1908, "In generalizing lies the difficulty of scientific map making, for it no longer allows the cartographer to rely merely on objective facts but requires him to interpret them subjectively" (p. 347). Other cartographers also have struggled with the intrinsic subjectivity of the generalization process as they have attempted to understand and define cartographic generalization. For instance, in 1942 John K. Wright argued that, "Not all cartographers are above attempting to make their maps seem more accurate than they actually are by drawing rivers, coasts, form lines, and so on with an intricacy of detail derived largely from the imagination" (p. 528). Wright identified two major components of the generalization process: simplification—the reduction of raw information that is

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too intricate—and amplification—the enhancement of information that is too sparse. This idea that generalization could be broken down into a logical set of processes, such as simplification and amplification, has become a common theme in generalization research.

Erwin Raisz (1962), for example, identified three major components of generalization: combination, omission, and simplification. Arthur Robinson and his colleagues (1978) identified four components: selection, simplification, classification, and symbolization. In Robinson et al.'s model, selection was considered a preprocessing step to generalization itself. Selection allowed for the identification of certain features and feature classes whereas generalization applied the various operations, such as simplification. This is detailed in their model, as discussed later.

6.2.2 Definitions of Generalization in the Digital Domain

In a digital environment, Robert McMaster and Stuart Shea (1992) noted that "the generalization process supports a variety of tasks, including: digital data storage reduction; scale manipulation; and statistical classification and symbolization. *Digital generalization* can be defined as the process of deriving, from a data source, a symbolically or digitally-encoded cartographic data set through the application of spatial and attribute transformations" (p. 3). McMaster and Shea listed the objectives of digital generalization as: (1) the reduction in scope and amount, type, and cartographic portrayal of mapped or encoded data consistent with the chosen map purpose and intended audience; and (2) the maintenance of graphical clarity at the target scale. The theoretical "problem" of generalization in the digital domain is straightforward: the identification of areas to be generalized and the application of appropriate operations, as discussed later.

6.3 MODELS OF GENERALIZATION

To better understand the complexity of generalization, researchers have attempted to design conceptual models of the process. Some efforts have focused on fundamental operations and the relationship among them, whereas others have created complex models.

6.3.1 Robinson et al.'s Model

Arthur Robinson and his colleagues (1978) developed one of the first formal models or frameworks to better understand the generalization process. They separated the process into two major steps: selection (a preprocessing step) and the actual process of generalization, which involves the geometric and statistical manipulation of objects. *Selection* involves the identification of objects to retain in (or eliminate from) the database. For instance, in developing content for a thematic map, often a minimal amount of base material is selected, such as major roads, political boundaries, or urbanized areas. Detailed base information, such as place names and hydrologic networks, are often eliminated because this base information is not deemed critical. On the other hand, considerable base information is often selected for detailed topographic maps, as this information is deemed critical. *Generalization* involves the processes of simplification, classification, and symbolization. Simplification is the elimination of unnecessary detail in a feature, classification involves the categorization of objects, and symbolization is the graphic encoding. Simplification is discussed further shortly, and both classification and symbolization are covered in other chapters in this book. In the 1970s, Joel Morrison (1974) formalized this series of steps (selection, simplification, classification, and symbolization) in the form of a set theory model. By applying set theory, he attempted to show how the basic data content was transformed through the generalization process. He defined each of the operations in terms of their set properties, including "one-to-one" (injective) and "onto" (surjective). For instance, if information is lost in the generalization process, then the relationship cannot be one-to-one. Although somewhat beyond the scope of this introductory book, the basic idea was to clarify the processes of generalization through formal mathematics.

6.3.2 Kilpeläinen's Model

Although the European literature contains numerous conceptual frameworks, few have had as significant an influence on American workers as the models of Tiina Kilpeläinen (1997) and Kurt Brassel and Robert Weibel (1988). Kilpeläinen developed alternative frameworks for the representation of multiscale databases. Assuming a master cartographic database, called the Digital Landscape Model (DLM), she proposed a series of methods for generating smaller scale Digital Cartographic Models (DCMs). The master DLM is the largest scale, most accurate database possible, whereas secondary DLMs are generated for smaller scale applications (Figure 6.1). The DLM is only a computer representation and cannot be visualized. DCMs, on the other hand, are the actual graphical representations, derived through a generalization or symbolization of the DLM. In her model, each DCM is generated directly from the initial master database or from the previous version. A separate DLM is created for each scale or resolution, and the DCM is directly generated from each DLM. The master DLM is used to generate smaller scale DLMs, which are then

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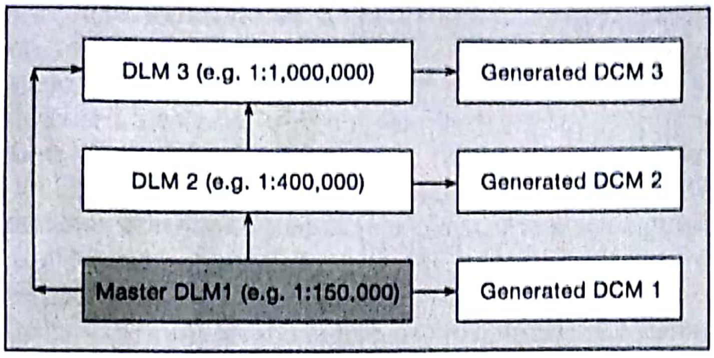

FIGURE 6.1 Kilpeläinen's notion of the Digital Landscape Model (DLM) and Digital Cartographic Model (DCM).

used to generate a DCM at that level. The assumption is that DCMs are generated on an as-needed basis.

6.3.3 Brassel and Weibel's Model

Brassel and Weibel (1988) have worked extensively at The University of Zurich in developing methods for terrain generalization. Their research has two primary objectives: to design a strategy for terrain generalization that is adaptive to different terrain types, scales, and map purposes, and to implement this strategy in an automated environment as fully as possible. Toward these ends, they have developed a model of terrain generalization that consists of five major stages: structure recognition, process recognition, process modeling, process execution, and data display and evaluation of results. In structure recognition, the specific cartographic objects—as well as their spatial relations and measures of importance—are selected from the source data. Process recognition identifies the necessary generalization operators and parameters by determining "specifically how the source data are to be transformed, which types of conflicts have to be identified and resolved, and which types of objects and structures have to be carried into the target database" (Weibel 1992, 134). Process modeling then compiles the rules and procedures—the exact algorithmic instructions—from a process library: a digital organization of these rules.

The final stages of Brassel and Weibel's model involve process execution, in which the rules and procedures are applied to create the generalization, data display, and finally, evaluation. Specifically, their model includes three different generalization methods: a global filtering, a selective (iterative) filtering, and a heuristic approach based on the generalization of the terrain's structure lines. For a given generalization problem that is constrained by the terrain character, map objective, scale, graphic limits, and data quality, the appropriate technique is selected through structure and process recognition procedures. The authors also depict the application of specific generalization operations, including selection, simplification, combination, and displacement, to illustrate the application of these operations to digital terrain models.

6.3.4 McMaster and Shea's Model

In an attempt to create a comprehensive conceptual model of the generalization process, McMaster and Shea (1992) identified three significant components: the theoretical objectives, or *why to generalize*; the cartometric evaluation, or *when to generalize*; and the fundamental operations, or *how to generalize* (Figure 6.2).

Why Generalization Is Needed: The Theoretical Objectives of Generalization

The theoretical or conceptual elements of generalization include reducing complexity, maintaining spatial accuracy, maintaining attribute accuracy, maintaining aesthetic quality, maintaining a logical hierarchy, and consistently applying the rules of generalization. Reducing complexity is perhaps the most significant goal of generalization. The question for the cartographer is relatively straightforward: How does one take a map at a scale of, perhaps, 1:24,000 and reduce it to 1:100,000? More important, the question is how the cartographer reduces the information content so that it is appropriate for the scale. Obviously, the complexity of detail that is provided at a scale of 1:24,000 cannot be represented at 1:100,000; some features must be eliminated and some detail must be modified. For centuries, through considerable experience, cartographers developed a sense of what constituted

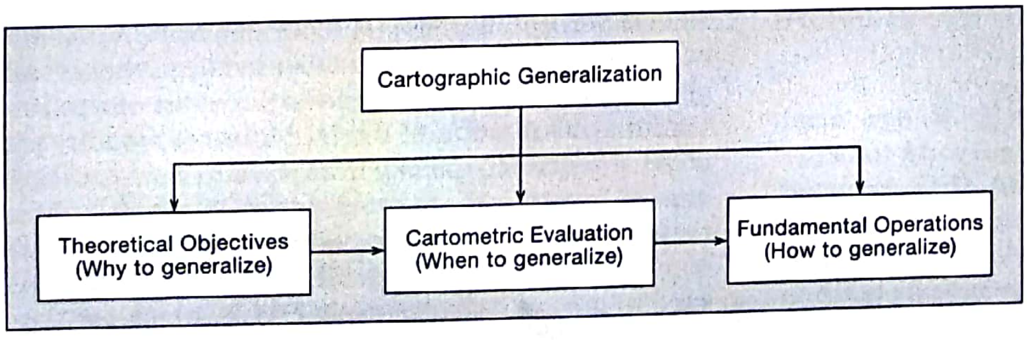

FIGURE 6.2 An overview of McMaster and Shea's model of generalization.

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appropriate information content. Figure 6.3 nicely illustrates this point. This figure depicts the very same feature—a portion of Ponta Creek in Kemper and Lauderdale Counties, Mississippi—at four different scales: 1:24,000, 1:50,000, 1:100,000, and 1:250,000. These features, digitized by Philippe Thibault (2002) in his doctoral dissertation, effectively show the significantly different information content as one reduces scale from 1:24,000 to 1:250,000. In the top portion of the illustration, the general form of the line stays the same, although the fine-level detail is lost. The bottom part of the illustration depicts an enlargement of the smaller scale features to match the feature at 1:24,000. Note, for instance, the enlargement of the 1:250,000 scale line by 1,041.67 percent to match Ponta Creek at 1:24,000. In this case, the cartographer has manually generalized Ponta Creek through a series of transformations including simplification, smoothing, and enhancement (as described later) as a holistic process, unlike current computer approaches that require a separation of these often linked processes. The set of decisions required to generalize cartographic features based on their inherent complexity is difficult if not impossible to quantify, although as described next, several attempts have been made over the past decade.

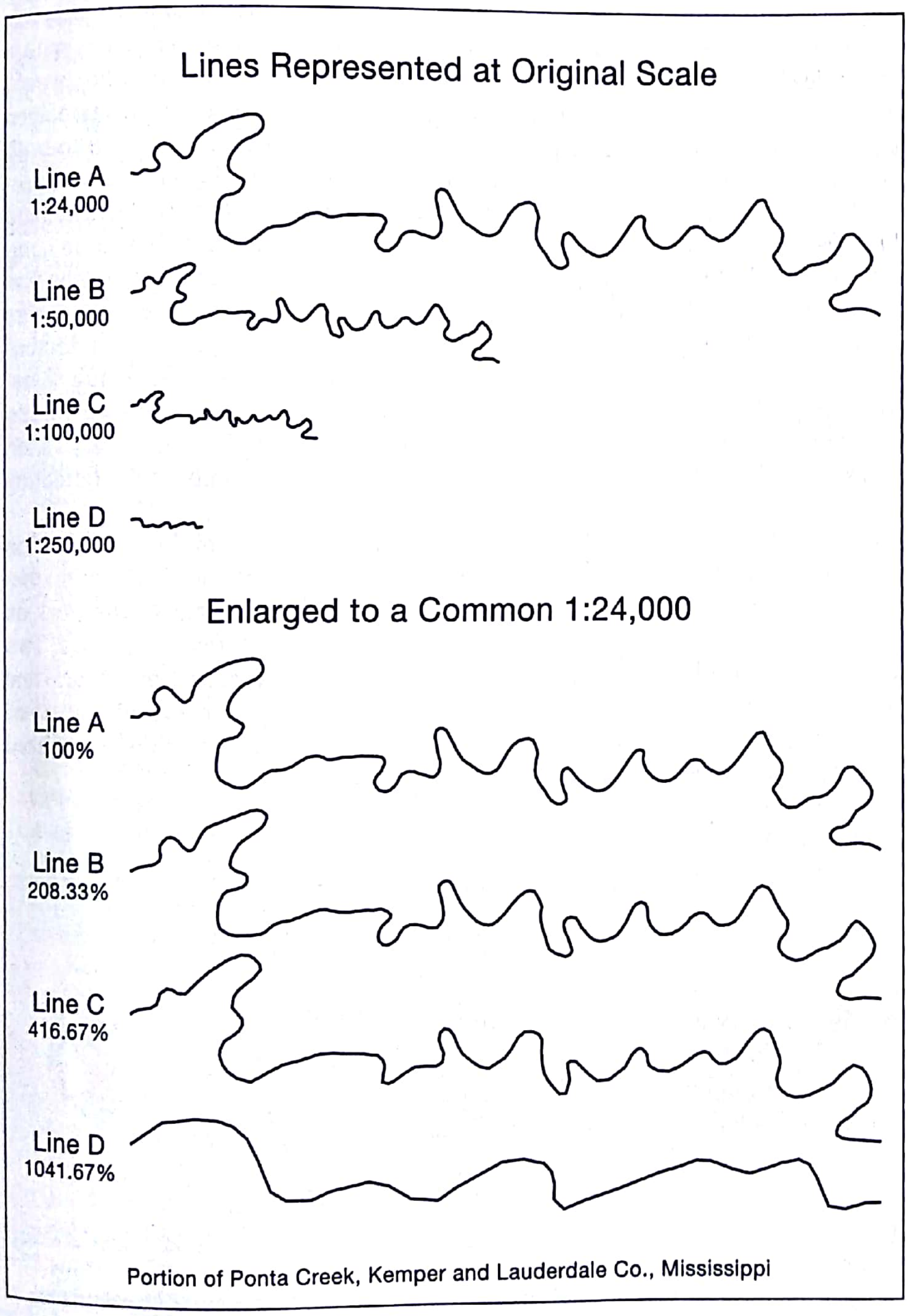

FIGURE 6.3 Depiction of Ponta Creek (in Mississippi) at four different scales. (Courtesy of Philippe Thibault.)

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Clearly, there is a direct and strong relationship among scale, information content, and generalization. John Hudson (1992) explained the effect of scale by indicating what might be depicted on a map 5 by 7 inches:

- A house at a scale of 1:100
- A city block at a scale of 1:1,000
- An urban neighborhood at a scale of 1:10,000
- A small city at a scale of 1:100,000
- A large metropolitan area at a scale of 1:1,000,000
- Several states at a scale of 1:10,000,000
- Most of a hemisphere at a scale of 1:100,000,000
- The entire world with plenty of room to spare at a scale of 1:1,000,000,000

He explained that these examples, which range from largest ($1:10^2$) to smallest ($1:10^9$), span eight orders of magnitude and a logical geographical spectrum of scales. Geographers work at a variety of scales, from the very large—the neighborhood—to the very small—the world. Generalization is a key activity in changing the information content so that it is appropriate for these different scales. However, a rough guideline that cartographers use is that scale change should not exceed 10×. Thus if you have a scale of 1:25,000, it should only be used for generalization up to 1:250,000. Beyond 1:250,000, the original data are "stretched" beyond their original fitness for use.

Two additional theoretical objectives important in generalization are maintaining the spatial and attribute accuracy of features. Spatial accuracy deals primarily with the geometric shifts that necessarily take place in generalization. For instance, in simplification coordinate pairs are deleted from the data set. By necessity, this shifts the geometric location of the features, creating "error." The same problem occurs with feature displacement, where two features are pulled apart to prevent a graphical collision. A goal in the process is to minimize this shifting and maintain as much spatial accuracy as possible. Attribute accuracy deals with the subject being mapped, or the statistical information such as population density or land use. For instance, classification, a key component of generalization, often degrades the original "accuracy" of the data through data aggregation.

When Generalization Is Required

In a digital cartographic environment, it is necessary to identify those specific conditions where generalization will be required. Although many such conditions can be identified, six of the fundamental conditions include:

1. Congestion
2. Coalescence
3. Conflict
4. Complication
5. Inconsistency
6. Imperceptibility

As explained by McMaster and Shea (1992), *congestion* refers to the problem when, under scale reduction, too many objects are compressed into too small a space, resulting in overcrowding due to high feature density (Figure 6.4). Significant congestion results in decreased communication, for instance, where too many buildings are in close proximity. *Coalescence* refers to the condition where features graphically collide due to scale change. In these situations, features actually touch. This condition thus requires the implementation of the displacement operation, as discussed shortly. The condition of *conflict* results when, due to generalization, an inconsistency between or among features occurs. For instance, if generalization of a coastline eliminated a bay with a city located on it, either the city or the coastline would have to be moved to ensure that the urban area remained on the coast. Such spatial conflicts are difficult to both detect and correct. The condition of *complication* is dependent on the specific conditions that exist in a defined space. An example is a digital line that changes in complexity from one part to the next, such as a coastline that progresses from very smooth to very crenulated, like Maine's coastline. Barbara Buttenfield (1991) demonstrated the use of line-geometry-based structure signatures as a means for controlling the tolerance values, based on complexity, in the generalization process. Later, details are provided on other techniques for detecting changes in linear complexity.

Despite the fact that many problems in generalization require the development and implementation of mathematical, statistical, or geometric measures, little work on generalization measurement has been reported. Two basic types of measures can be identified: procedural and quality assessment. Additionally, some measures are used to assess individual features, whereas others are utilized in a more global manner.

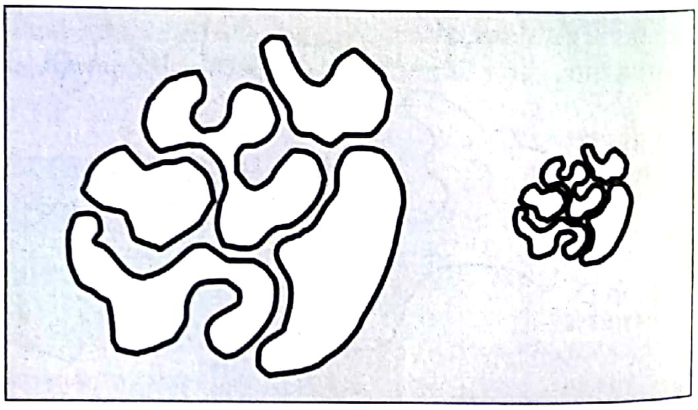

FIGURE 6.4 How a change in scale can create congestion.

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Procedural measures are those needed to invoke and control the process of generalization. Such measures might include those to: (1) select a simplification algorithm, given a certain feature class; (2) modify a tolerance value along a feature as the complexity changes; (3) assess the density of a set of polygons being considered for agglomeration; (4) determine whether a feature might undergo a type change (e.g., area to point) due to scale modification; and (5) compute the curvature of a line segment to invoke a smoothing operation. *Quality assessment measures* evaluate both individual operations, such as the effect of simplification, and the overall quality of the generalization (e.g., poor, average, excellent). Several studies have reported on mathematical and geometric measures, including Buttenfield (1991), McMaster (1986; 1987) and Plazanet (1995), yet no comprehensive framework of the existing and potential measures and their characteristics has been developed.

One general classification of measures, as presented by McMaster and Shea (1992), includes the following classes: density, distribution, length and sinuosity, shape, distance, and Gestalt.

- *Density measures* are used to evaluate multifeature relationships, and can include such metrics as the number of point, line, or area features per unit area; average density of point, line, or area features; and the number and location of centroids of point, line, or area features. An example of a density measure for urban blocks might be the number of blocks within a 500-meter radius. The lakes region of northern Minnesota, the Thousand Islands in the St. Lawrence Seaway, and the deltaic region of the Mississippi River are all examples of geometries where a high degree of complexity might need simplification. European researchers apply density measures to complex building configurations in cities to delete or fuse structures together. A complicating factor here, of course, is the actual configuration and number of buildings in an urban environment. Jones et al. (1995) detailed a series of measures for such built structures based on their data structure.
- *Distribution measures* are used to assess the overall spatial configuration of the map features. For example, we might measure the dispersion, randomness, and clustering of point features. Linear features can be assessed by their overall pattern—an example would be the calculation of the distribution of a stream network based on the number of first-, second-, and third-order streams, or whether the pattern is dendritic or trellis. In a similar way, areal features can be evaluated by their intrinsic distribution, such as the spatial configuration of a series of islands.
- *Length and sinuosity measures* are often applied to single linear or areal boundary features such as the calculation of stream network lengths. Some sample length measures include total number of coordinate pairs, total length, and the average number of coordinates or standard deviation of coordinates per inch. Sinuosity measures can include total angular change, average angular change per inch, average angular change per angle, sum of positive or negative angles, and total number of positive and negative turns (McMaster 1986). One common sinuosity measure involves calculating the individual angularity between segments, often noted as either positive or negative (Figure 6.5). Another sinuosity measure accumulates these into curvilinear segments, defined as continuous runs, or turns, of positive or negative angles. Yet another measure, as described in more detail later, computes the trend line along the curves to create a medial trend line. Additionally, specific measures for feature classes have been designed in various domains of knowledge, such as common morphometric measurements compiled from physical geography, hydrology, and geology.
- *Shape measures* have been commonly applied in the geographic literature for measuring the form of objects, and are useful in the determination of whether an area feature can be represented at a new scale (Christ 1976). In general, the most important components of shape are the overall elongation of the polygon and the efficiency or sinuosity of its boundary, but many metrics can be used: geometry of point, line, or area features; perimeter of area features; centroid of line or area features, X and Y variances of area features, covariance of X and Y area features, and the standard deviation of X and Y area features (Bachi 1973). One of the best-known shape measures was developed by Boyce and Clarke (1964). Called the radial line method, it calculates the lengths of a set of radials (the number of radials is user defined) from the centroid of a polygon to the edges of the boundary. These accumulated lengths are then compared to the set of lengths that would be expected on the most regularized form—the circle. The larger the index

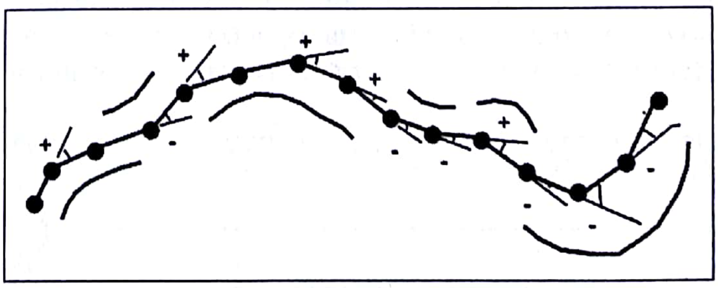

FIGURE 6.5 A common sinuosity measure involves calculating the individual angularity between segments making up a line.

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value, the more the shape varies from a circle. Such a method could be applied to a series of polygons to assess basic complexity and need for generalization. Other commonly used measures compute relationships between the area and perimeter of polygons (Muehrcke et al. 2001, 358–359).

- *Distance measures* involve computing the distance between the basic geometric forms—points, lines, and areas. Distances between each of these forms can be assessed by examining the shortest perpendicular distance or shortest Euclidean distance between each form. In the case of two geometric lines, two different distance calculations exist: (1) line-to-line and (2) line buffer-to-line buffer. Figure 6.6, for instance, shows a simple straight line and the line's buffer, which is equidistant from the line itself. Such buffers are commonly used in GISs to measure the proximity of features. Distance measures related to buffers are crucial for many fundamental operations of generalization; for instance, under scale reduction the features or their respective buffers might be in conflict.
- *Gestalt measures* are based in the use of Gestalt theory, which helps to indicate perceptual characteristics of the feature distributions through an isomorphism—that is, the structural relationship that exists between a stimulus pattern and the expression it conveys (Arnheim 1974). Common examples of this relationship include closure, continuation, proximity, and similarity (Wertheimer 1958). Although the existence of these Gestalt characteristics is well documented, few techniques have been developed that would accurately serve to identify them.

6.4 THE FUNDAMENTAL OPERATIONS OF GENERALIZATION

6.4.1 A Framework for the Fundamental Operations

In the McMaster and Shea model discussed earlier, the third major component involves the fundamental operations or how to generalize. Most of the research in generalization assumes that the process can be broken down into a series of logical operations that can be classified according to the type of geometry of the feature. For instance, a simplification operation is designed for linear features, whereas an amalgamation operator works on areal features. Table 6.1 provides a framework for the operations of generalization, dividing the process into those activities for vector- and raster-mode processing. The types of generalization operations for vector and raster processing are fundamentally different. Vector-based operators require more complicated strategies because they operate on strings of x–y coordinate pairs and require complex searching strategies. In raster-based generalization, it is much easier to determine the proximity relationships that are often the basis for determining conflict among the features. Next, a more detailed discussion of individual vector-based operations is provided, and Figure 6.7 provides graphic depictions of some key operations.

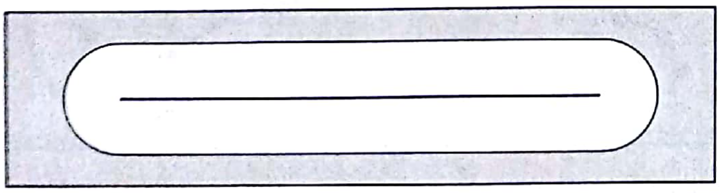

FIGURE 6.6 A line and its buffer, which is equidistant from the line.

6.4.2 Vector-Based Operations

Simplification

Simplification is the most commonly used generalization operator. The concept is relatively straightforward, because it involves at its most basic level a "weeding" of unnecessary coordinate data. The goal is to retain as much of the geometry of the feature as possible, while eliminating the maximum number of coordinates. Most simplification routines utilize complex geometrical criteria (distance and angular measurements) in selecting significant or critical points. A general classification of simplification methods consists of five approaches: independent point routines, local processing routines,

TABLE 6.1 A framework for generalization operations (After McMaster and Monmonier 1989, and McMaster 1989b.)

Raster-mode generalization	Vector-mode generalization
Structural generalization	Point feature generalization
Simple structural reduction	Aggregation
Resampling	Displacement
Numerical generalization	Line feature generalization
Low-pass filters	Simplification
High-pass filters	Smoothing
Compass gradient masks	Displacement
Vegetation indices	Merging
	Enhancement
Numerical categorization	Areal feature generalization
Minimum-distance to means	Amalgamation
Parallelopiped	Collapse
Maximum-likelihood classification	Displacement
Categorical generalization	Volume feature generalization
Merging (of categories)	Smoothing
Aggregation (of cells)	Enhancement
Nonweighted	Simplification
Category-weighted	
Neighborhood-weighted	
Attribute change	
	Holistic generalization
	Refinement

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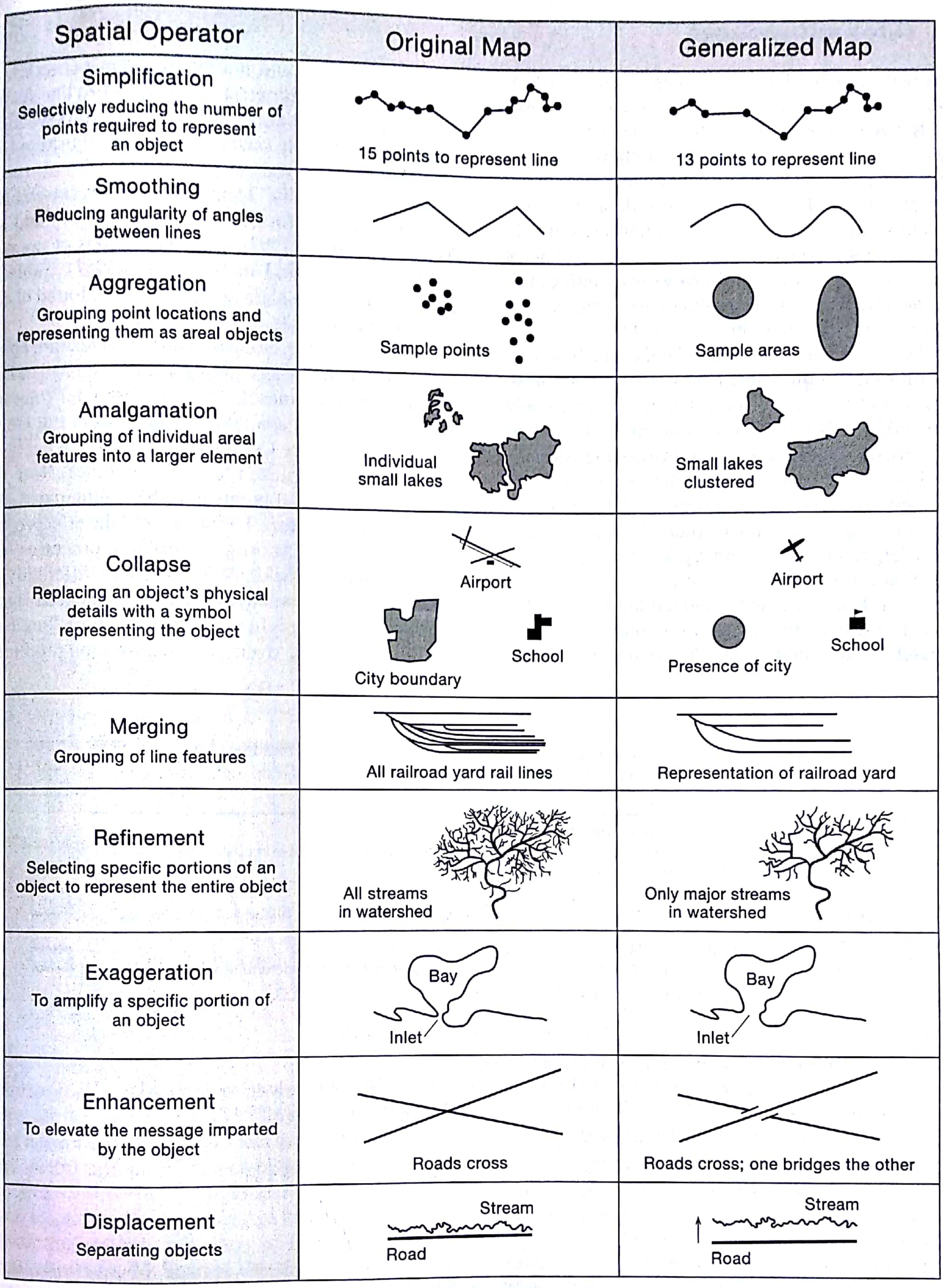

FIGURE 6.7 Fundamental operations of generalization. (Courtesy of Philippe Thibault.)

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constrained extended local processing routines, unconstrained extended local processing routines, and global methods. **Independent point routines** select coordinates based on their position along the line, nothing more. For instance, a typical *n*th point routine might select every third point to quickly weed coordinate data. Although computationally efficient, these algorithms are crude in that they do not account for the true geomorphological significance of a feature. **Local processing routines** utilize immediate neighboring points in assessing the significance of the point. Assuming a point to be simplified x_n, y_n, these routines evaluate its significance based on the relationship to the immediate neighboring points, x_{n-1}, y_{n-1}, and x_{n+1}, y_{n+1}. This relationship is normally determined by either a distance or angular criterion, or both. **Constrained extended local processing routines** search beyond the immediate neighbors and evaluate larger sections of lines, again normally determined by distance and angular criteria. Certain algorithms search around a larger number of points, perhaps two, three, or four in either direction, whereas others use more complex criteria. **Unconstrained extended local processing routines** also search around larger sections of a line, but the search is terminated by the geomorphological complexity of the line, not by algorithmic criterion. Finally, **global algorithms** process the entire line feature at once and do not constrain the search to subsections. The most commonly used simplification algorithm—the Douglas–Peucker—takes a global approach and processes a line "holistically." Details of the Douglas–Peucker algorithm can be found in McMaster (1987) and McMaster and Shea (1992), and comparisons of the algorithms can be found in McMaster (1987). Table 6.2 provides details on algorithms that can be found in each of the five categories.

The effect of the Douglas–Peucker algorithm can be seen in Figure 6.8, where the algorithm is applied to Hennepin County, Minnesota, using a 350-meter tolerance value. The original spatial data, taken from the United States Bureau of the Census TIGER files, is in light gray, whereas the generalized feature is in black. Note that many of the original points have been eliminated, thus simplifying the feature. Unfortunately, the effects of this approach—as with most generalization processes—are not consistent, as the algorithm behaves differently depending on the geometric or geomorphological significance of the feature. In areas that are more "natural," such as streams and rivers, the simplification produces a

TABLE 6.2 A classification of algorithms used to simplify cartographic features (After McMaster and Shea, 1992, *Generalization in Digital Cartography*. p. 73, copyright Association of American Geographers.)

Category 1:	Independent point algorithms Do not account for the mathematical relationships with the neighboring pairs, operate independent of topology		
		Examples:	*N*th point routine Random selection of points
Category 2:	Local processing routines Utilize the characteristics of the immediate neighboring points in determining significance		
		Examples:	Distance between points Angular change between points Jenks's algorithm (distance and angular change)
Category 3:	Constrained extended local processing routines Search continues beyond immediate coordinate neighbors and evaluates sections of a line Extent of search depends on distance, angular, or number of points criterion		
		Examples:	Lang algorithm Opheim algorithm Johannsen algorithm Deveau algorithm Roberge algorithm Visvalingam algorithm
Category 4:	Extended local processing routines Search continues beyond immediate coordinate neighbors and evaluates sections of a line Extent of the search is constrained by geomorphological complexity of the line, not by algorithmic criterion		
		Example:	Reumann–Witkam algorithm
Category 5:	Global routines Considers the entire line, or specified line segment; iteratively selects critical points		

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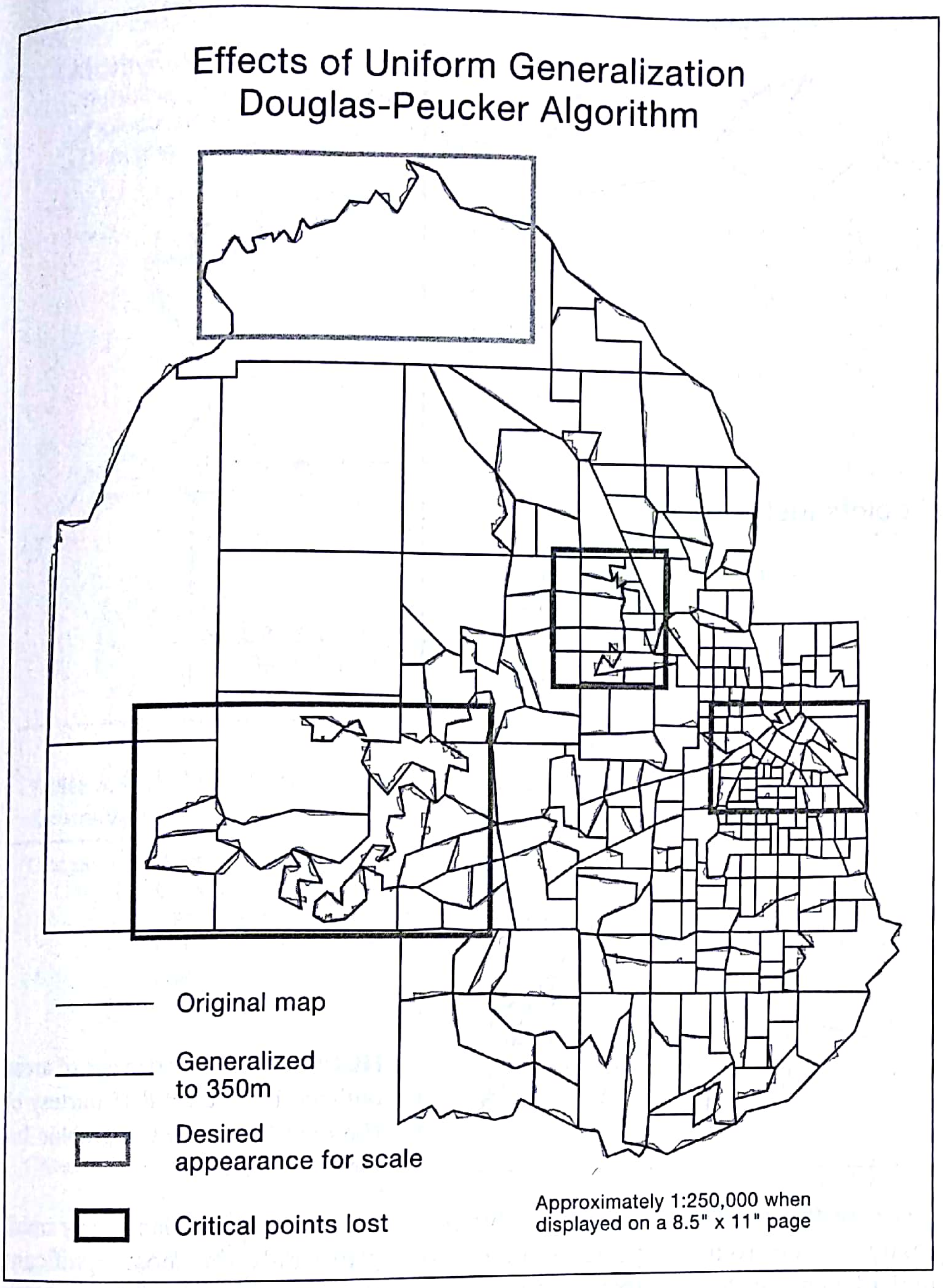

FIGURE 6.8 Overview of effects of Douglas–Peucker simplification in Hennepin County, Minnesota. (After McMaster, R. B., and Sheppard, E. (2004) "Introduction: Scale and Geographic Inquiry," p. 9. In *Scale and Geographic Inquiry: Nature, Society and Method,* ed. by E. Sheppard and R. B. McMaster. Courtesy of Blackwell Publishing.)

relatively good approximation. However, in urban areas, where the census geography follows the rectangular street network, the results are less satisfactory. In many cases, logical right angles are simplified to diagonals.

Figure 6.9 shows an enlargement of several parts of Figure 6.8. At the top, it is clear that the algorithm works well on the northern boundary of Hennepin County, which follows the Mississippi River. The bottom three enlargements depict where essential critical points have been lost, resulting in simplifications that are not deemed acceptable. A significant problem in the generalization process involves the identification of appropriate tolerance values for simplification. Unfortunately, this is mostly an experimental process, where the user has to test and retest values until an acceptable solution is empirically found. As explained previously, cartographers often turn to measurements to ascertain the complexity of a feature and to assist in establishing appropriate tolerance values.

Figure 6.10 depicts the calculation of one specific measurement, the *trendline*, for the Hennepin County data set. The trendlines for a digitized curve are based on a calculation of angularity, or where the lines change direction. Where a curve changes direction, for example, from left to right, a mathematical inflection point is defined (theoretically, the point of no curvature). The connection of these inflection points, which indicates the general "trend" of the line, is called the trendline. The complexity of a feature can be approximated by looking

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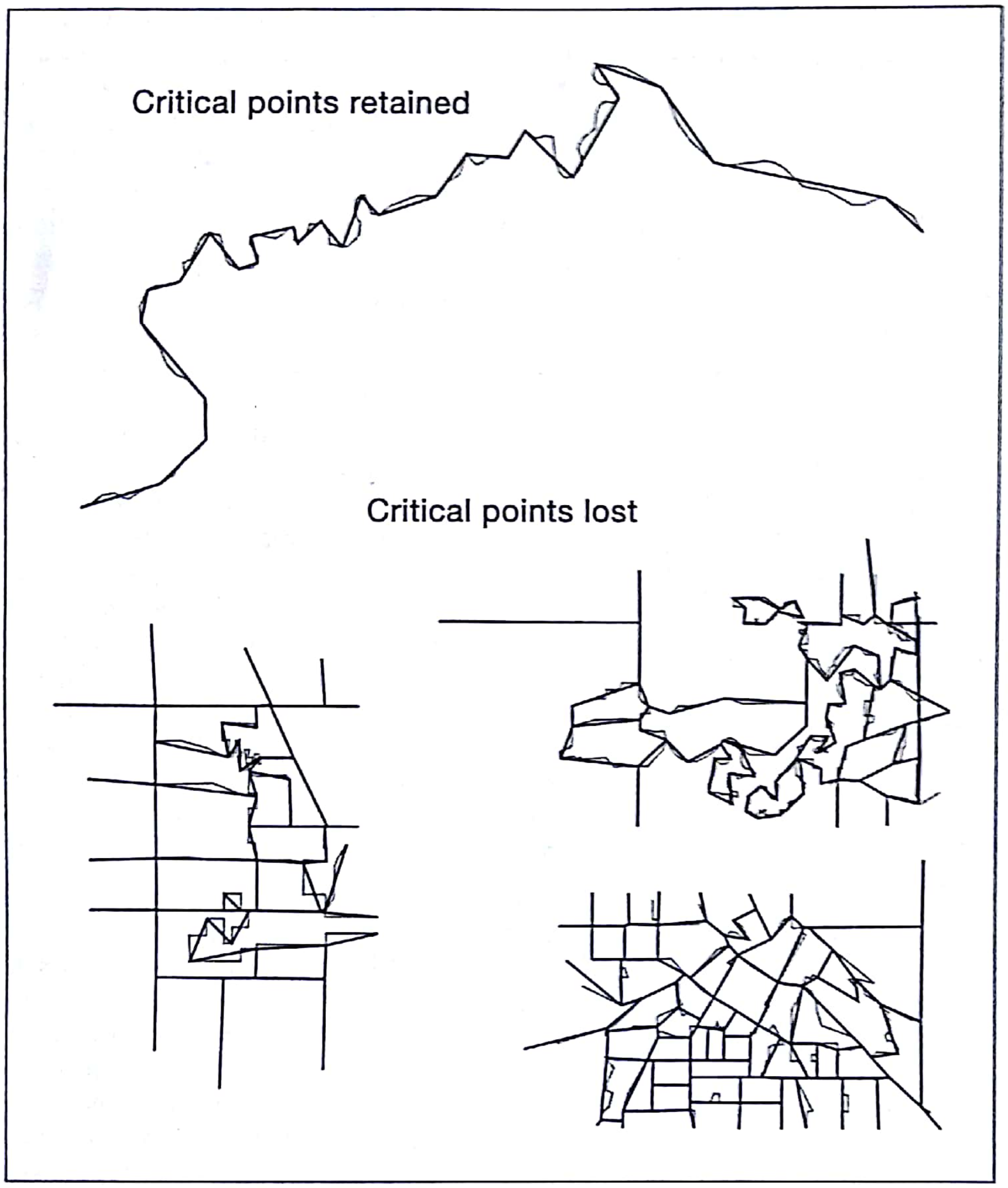

FIGURE 6.9 Enlargements of areas outlined in Figure 6.8. (Courtesy of National Historical Geographic Information System.)

at the trendlines for an entire feature or for the entire data set. A simple measure of complexity derived from the trendline is the trendline/total length of a line, or the sinuosity of a feature. Along relatively straight line segments, with little curvalinearity, the trendline will be very close to the curve and the trend line/total length ratio will be nearly the same (e.g., the relatively straight line near the middle of Figure 6.10). However, a highly complex curve, such as the northern border of Hennepin County, will deviate significantly from the trendline, and the length of the trendline will be greater. Thus, the greater the difference between the actual digitized curve and the trendline, the more complex the feature.

Smoothing

Although often assumed to be identical to simplification, **smoothing** is a much different process. The smoothing operation shifts the position of points to improve the appearance of the feature (Figure 6.7). Smoothing algorithms relocate points in an attempt to plane away small perturbations and capture only the most significant trends of the line (McMaster and Shea 1992). As with simplification, there are many approaches for the process—a simple classification is provided in Table 6.3.

Research has shown that a careful integration of simplification and smoothing routines can produce a simplified, yet aesthetically acceptable, result (McMaster 1989a).

Aggregation

As depicted in Figure 6.7, **aggregation** involves the joining together of multiple point features, such as a cluster of buildings. This process involves grouping point locations and representing them as areal units. The critical problem in this operation is determining both the density of points needed to identify a cluster to be aggregated and the boundary around the cluster. The most common approach is to create a Delaunay triangulation of points and use measures of distance along the

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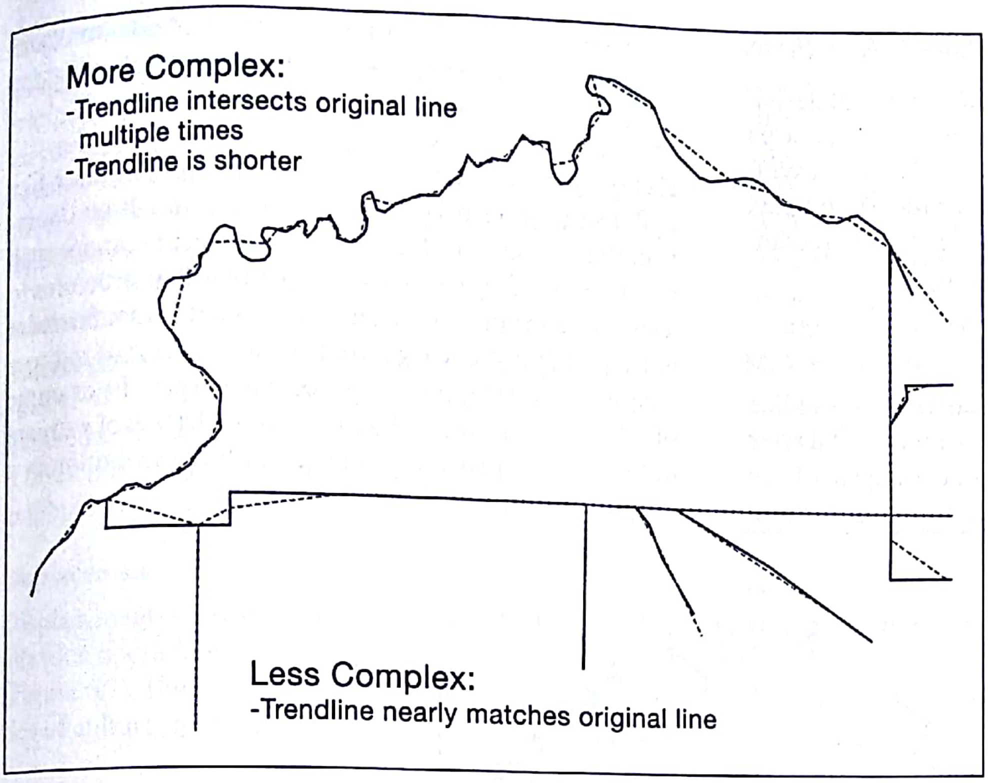

FIGURE 6.10 Comparison of the original unsimplified line and a trend-line, an indicator of the degree of simplification. The image is of the northern portion of Hennepin County shown in Figure 6.8. (Courtesy of National Historical Geographic Information System.)

TABLE 6.3 A classification of algorithms used to smooth cartographic features (After McMaster and Shea 1992, *Generalization in Digital Cartography*, pp. 86–87, copyright Association of American Geographers.)

Category 1:	Weighted averaging Calculates an average value based on the positions of existing points and neighbors, with only the end points remaining the same; maintains the same number of points as the original line; algorithms can be easily adopted for different smoothing conditions by adjusting tolerance values (e.g., number of points used in smoothing); all algorithms use local or extended processors Examples: Three-point moving average Five-point moving average Other moving average methods Distance-weighted averaging Slide averaging
Category 2:	Epsilon filtering Algorithm uses certain geometrical relationships between the points and a user-defined tolerance to smooth the cartographic line; endpoints are retained, but the absolute number of points generated for the smoothed line is algorithm dependent; approaches are local, extended local, and global Examples: Epsilon filtering Brophy algorithm
Category 3:	Mathematical approximation Develop a mathematical function or series of mathematical functions that describe the geometrical nature of the line; number of points on the smoothed line is variable and is controlled by the user; retention of the endpoints and of the points on the original line is dependent on the choice of algorithms and tolerances; function parameters can be stored and used to later regenerate the line at the required point density; approaches are local, extended local, and global Examples: Local processing: cubic spline Extended local processing: b-spline Global processing: bezier curve

Delaunay edges to calculate density and boundary (Jones et al., 1995).

Amalgamation

Amalgamation is the process of fusing together nearby polygons, and is needed for both noncontinuous and continuous areal data (Figure 6.7). A noncontinuous example is a series of small islands in close proximity with size and detail that cannot be depicted at the smaller scale. A continuous example is with census tract data, where several tracts with similar statistical attributes can be joined together. Amalgamation is a very difficult problem in urban environments where a series of complex buildings might need to be joined.

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Collapse

The **collapse** operation involves the conversion of geometry. For instance, it might be that a complex urban area is collapsed to a point due to scale change and resymbolized with a geometric form, such as a circle. A complex set of buildings may be replaced with a simple rectangle—which might also involve amalgamation.

Merging

Merging is the operation of fusing together groups of line features, such as parallel railway lines, or edges of a river or stream (Figure 6.7). This is a form of collapse, where an areal feature is converted to a line. A simple solution is to average the two or multiple sides of a feature, and use this average to calculate the new feature's position.

Refinement

Refinement is another form of resymbolization, much like collapse (Figure 6.7). However, refinement is an operation that involves reducing a multiple set of features such as roads, buildings, and other types of urban structures to a simplified representation. The concept with refinement is that such complex geometries are resymbolized to a simpler form, a "typification" of the objects. The example of refinement shown in Figure 6.7 is a selection of a stream network to depict the "essence" of the distribution in a simplified form.

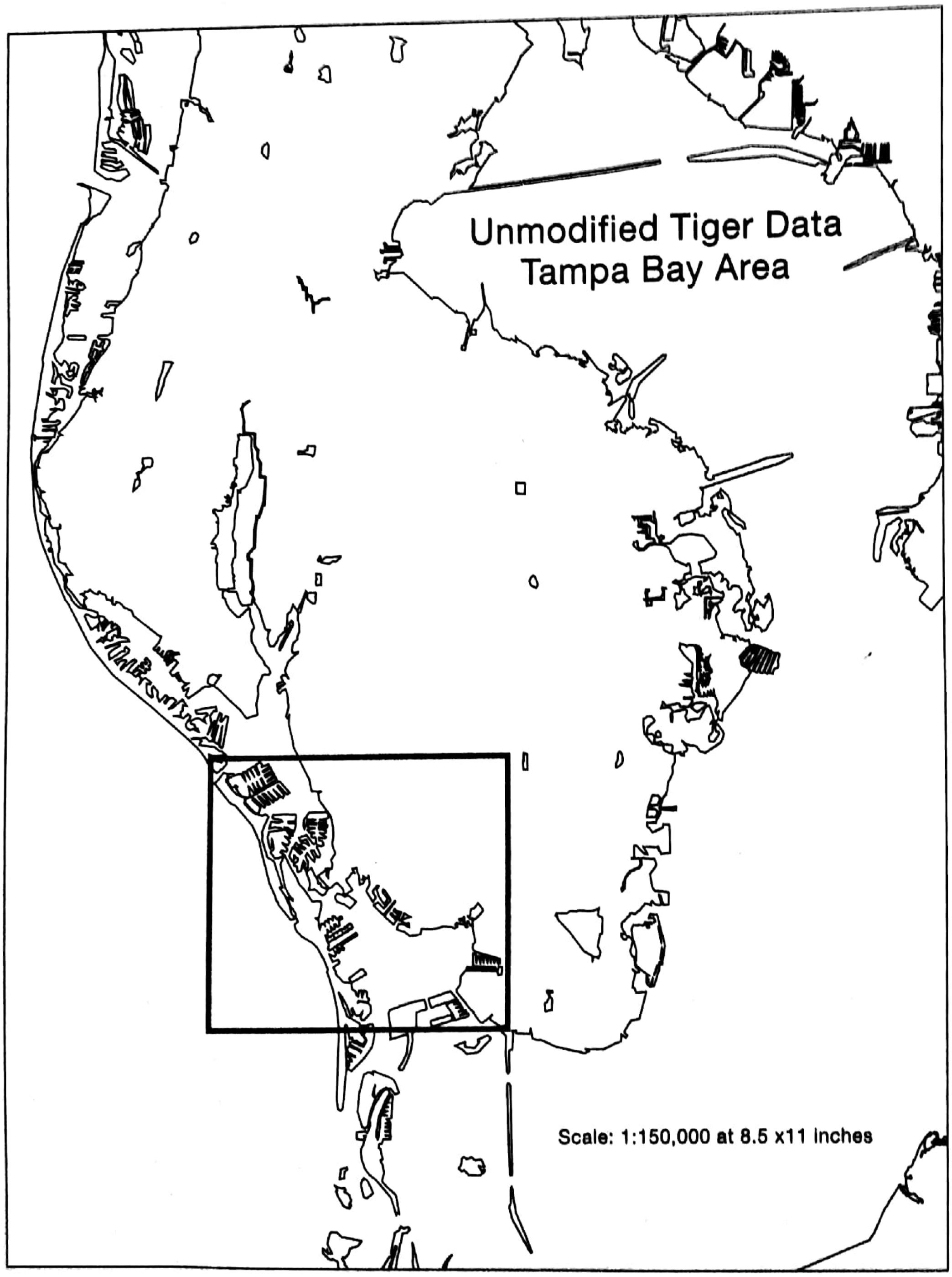

FIGURE 6.11 Unsimplified representation of the Tampa Bay-St. Petersburg, Florida, region at a scale of 1:150,000 when displayed on a 8.5″ × 11″ page. (Courtesy of National Historical Geographic Information System.)

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Exaggeration

Exaggeration is one of the more commonly applied generalization operations. Often it is necessary to amplify a specific part of an object to maintain clarity in scale reduction. The example in Figure 6.7 depicts the exaggeration of the mouth of a bay that would close under scale reduction.

Enhancement

Enhancement involves a symbolization change to emphasize the importance of a particular object. For instance, the delineation of a bridge under an existing road is often portrayed as a series of cased lines that assist in emphasizing that feature over another.

Displacement

Displacement is perhaps the most difficult of the generalization operations, as it requires complex measurement (Figure 6.7). The problem might be illustrated with a series of cultural features in close proximity to a complex coastline. Assume, for example, that a highway and railroad follow a coastline in close proximity, with a series of smaller islands offshore. In the process of scale reduction, all features would tend to coalesce. The operation of displacement would pull these features apart to prevent this coalescence. What is critical in the displacement operation is the calculation of a displacement hierarchy because one feature will likely have to be shifted away from another (Nickerson and Freeman 1986; Monmonier and McMaster 1990). A description of the mathematics involved in displacement can be found in McMaster and Shea (1992).

6.5 AN EXAMPLE OF GENERALIZATION

Figure 6.11 depicts the raw TIGER vector data for the Tampa-St. Petersburg area of Florida. These data, encoded at a scale of 1:150,000, show the complexity of both the natural and human-created coastline along the Florida coast. Figure 6.12 depicts a simplification of the inset

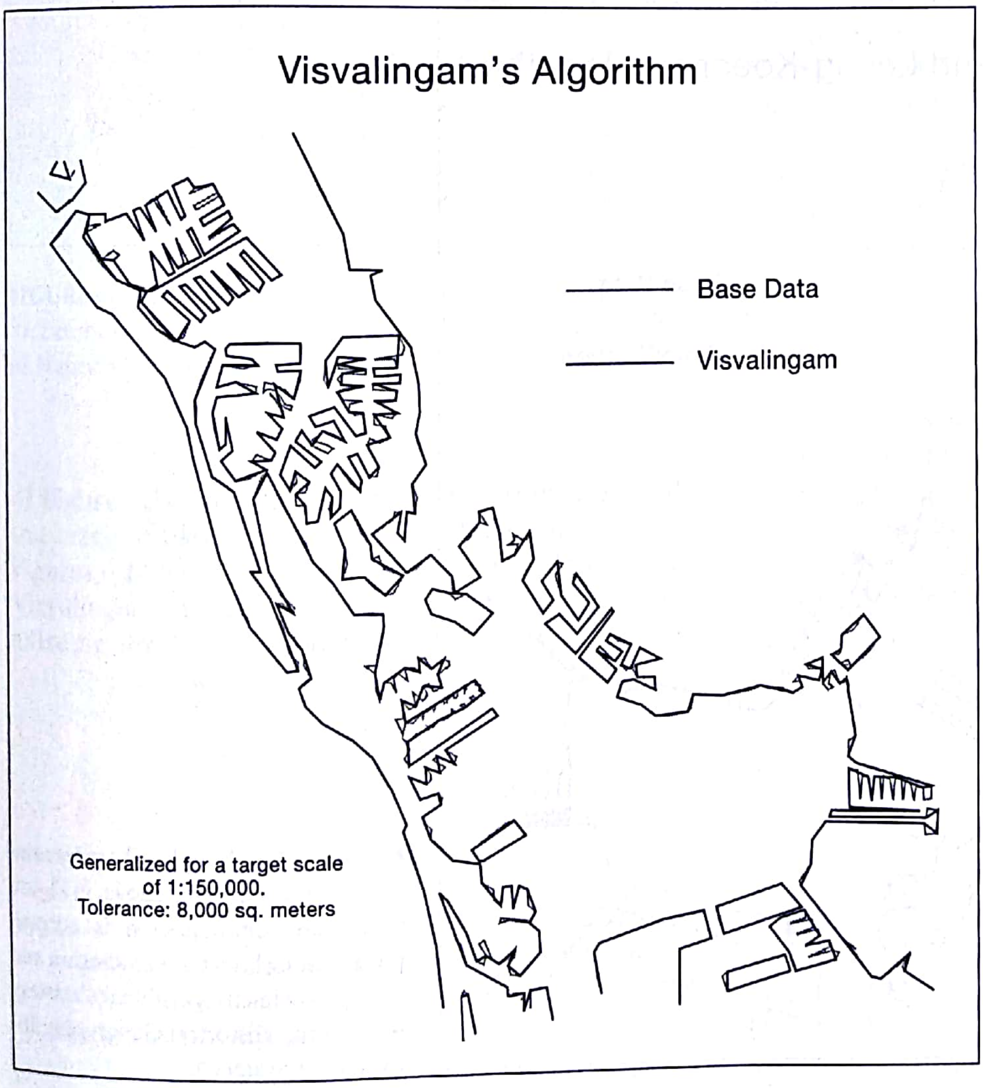

FIGURE 6.12 Simplified representation of the inset region shown in Figure 6.11; here simplification is accomplished using Visvalingam's algorithm. (Courtesy of National Historical Geographic Information System.)

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area in Figure 6.11 using the Visvalingam algorithm (Visvalingam and Williamson 1995), which uses an areal tolerance (in this case 8,000 square meters) to select critical points and is considered to be robust in maintaining the original character of the line. This is a somewhat novel approach in that most simplification algorithms use a linear distance to determine the proximity between the original feature and the simplified version. An areal tolerance measures the "area" of change as points are eliminated and the two features are displaced. When this area is too large, based on the user-defined tolerance, no further points are eliminated. Note in particular the performance of the simplification algorithm along the complicated "canaled" coastline, where it becomes difficult to retain the rectangular nature of this human-created landscape.

Although considerable developments in automated generalization have taken place over the last 30 years, it is still difficult to solve generalization problems with off-the-shelf software due to the limited capability of the algorithms and complexity of the databases. At the National Historical Geographic Information System (NHGIS) project at the University of Minnesota (*http://www.nhgis.org/*), work is currently underway to design generalization software for specific problems, such as this coastline example. One algorithm, developed by Kai Chi Leung and programmed by Ryan Koehnen, is designed to retain the critical right angle geometry of such landscapes, while also reducing the number of canals. Figure 6.13 shows the same inset as before, but with both the Visvalingam and Leung–Koehnen algorithms applied. Note that many of the smaller canals have been generalized, and are now aggregated into larger units that will more easily be reduced through scale change.

A major goal of the NHGIS project is to provide multiple scale versions of census data to enable users to select the scale most appropriate for their use. To illustrate, consider Figure 6.14, which again depicts the Tampa-St. Petersburg area of Florida, but is intended to appear at a scale of 1:400,000; an enlargement of the central portion

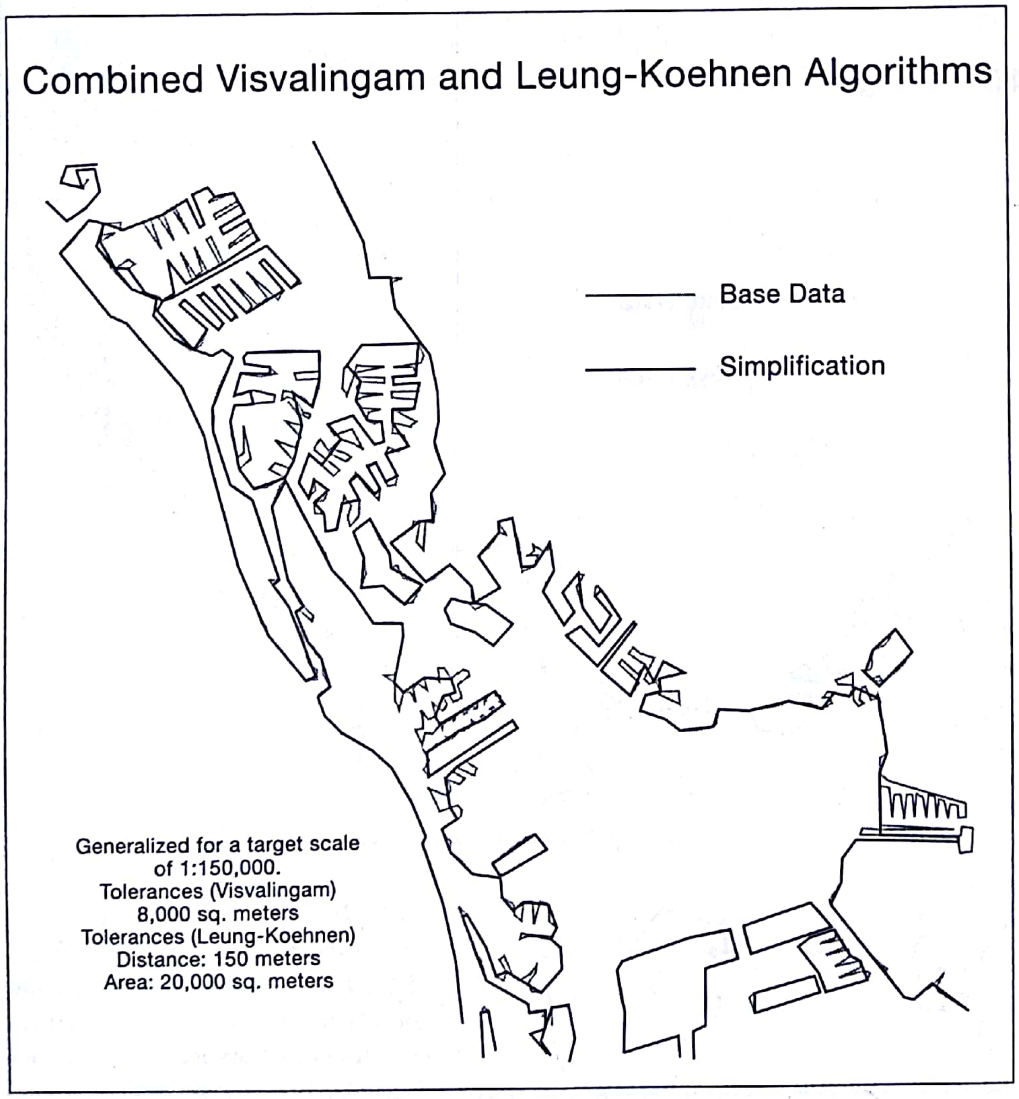

FIGURE 6.13 Simplified representation of the inset region shown in Figure 6.11; here simplification is accomplished using both the Visvalingam and Leung–Koehnen algorithms. (Courtesy of National Historical Geographic Information System.)

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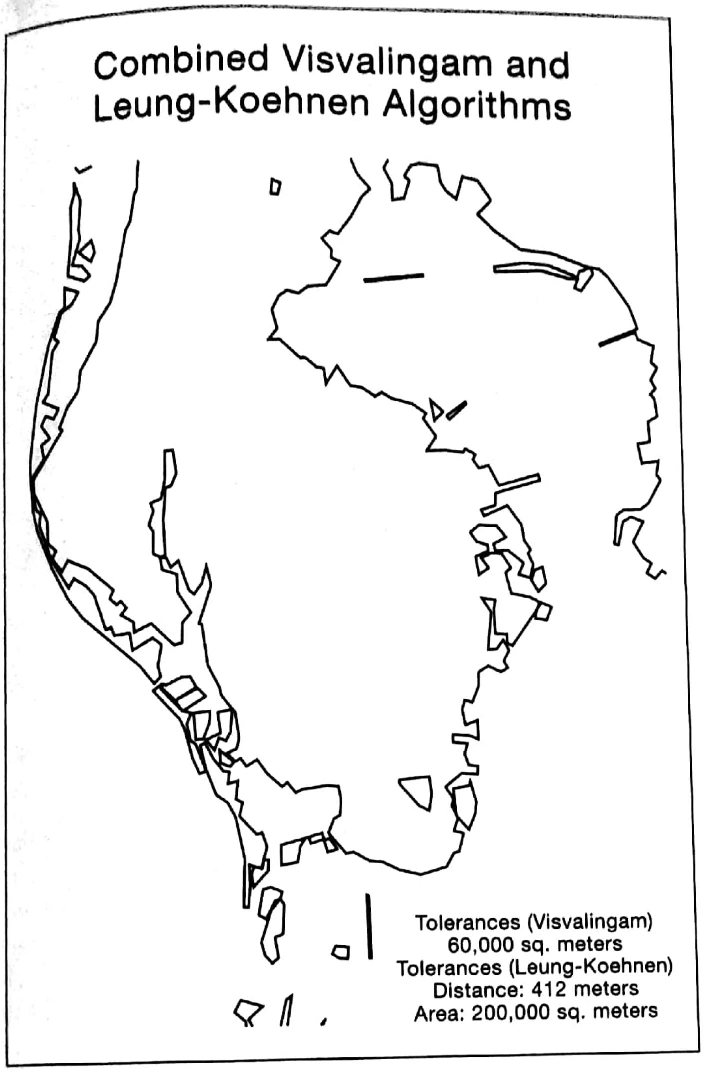

FIGURE 6.14 Generalized representation of the Tampa Bay-St. Petersburg, Florida, region shown in Figure 6.11. (Courtesy of National Historical Geographic Information System.)

of Figure 6.14 including both the generalization and the original base data is shown in Figure 6.15. Both Figures 6.14 and 6.15 have been generalized using the Visvalingam and Leung–Koehnen algorithms. Note the extreme level of generalization here, with only the significant parts of the coastline retained. For such problems it is often necessary to look beyond standard approaches and create custom-designed solutions.

SUMMARY

Scale is a fundamental process in geography and cartography. It requires the cartographer to select the appropriate information content given the map purpose and intended audience. The set of processes used to manipulate (change the scale of) the spatial information are collectively known as **generalization**. Cartographers have tackled the problem of generalization for centuries in the manual domain, but conversion to the digital world has created many new challenges. This chapter has provided a discussion of the various forms of scale, including **cartographic scale**, which is depicted with the representative fraction, such as 1:24,000. It should be noted, however, that geographers and other spatial scientists often conceptualize scale very differently, such as human geographers' views on the social construction or political construction of scale.

We reviewed major definitions and models of the generalization process. Generalization models include those by Robinson and his colleagues, Morrison, Weibel and Brassel, and McMaster and Shea. We have provided details of the McMaster and Shea model, which was designed for the generalization process in a digital environment. A critical part of the generalization process involves the identification and implementation of the fundamental operations, such as line **simplification**. For each of the operations, multiple approaches or computer algorithms have been designed, such as the Douglas and Peucker simplification routine. Fuller details of most algorithms can be found in the cartographic, geographic, and computer science literature.

Finally, we provided an example of generalization using ongoing work at the National Historic Geographic Information System (NHGIS), housed at the University of Minnesota. Here we saw that the complexity of the real world often requires the creation of custom-designed solutions.

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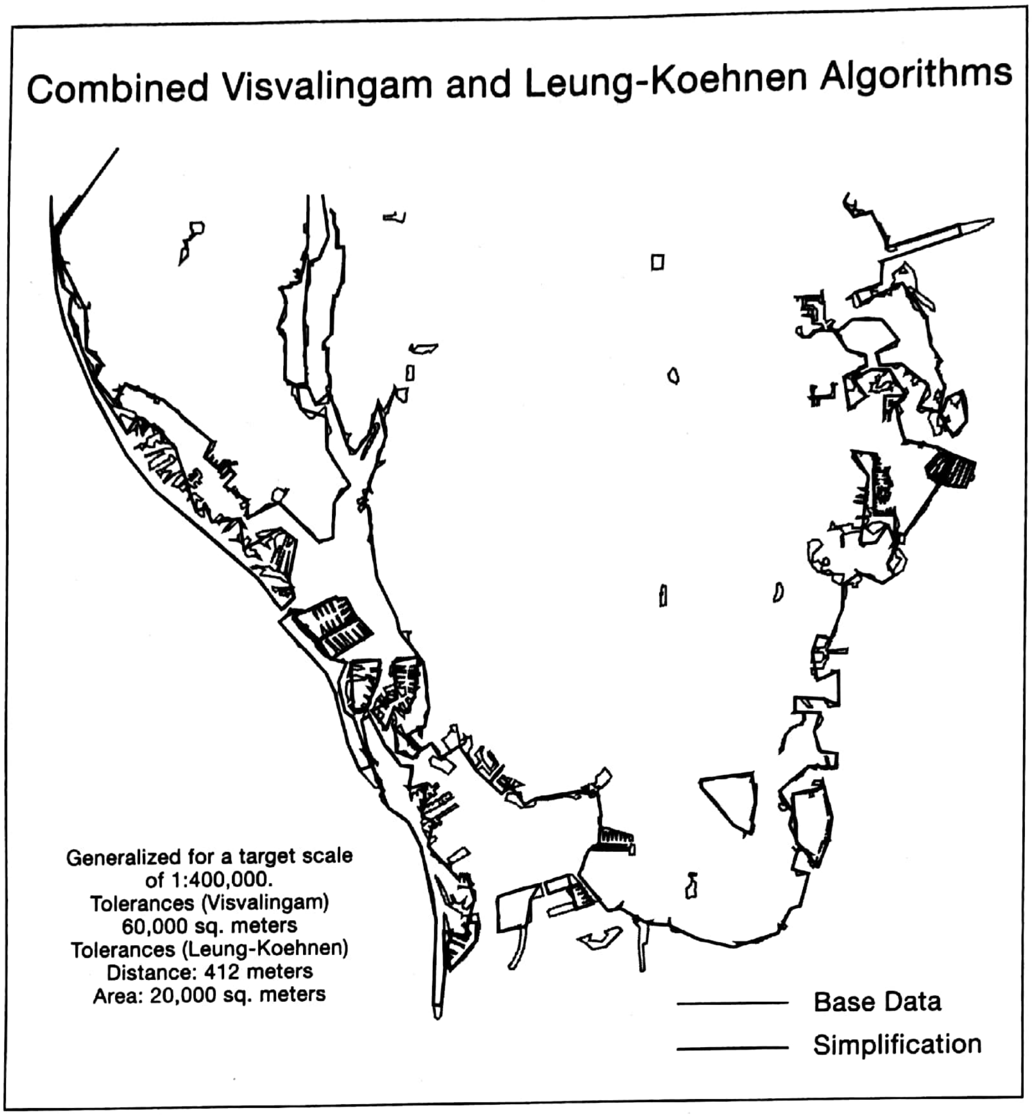

FIGURE 6.15 An enlargement of the lower left portion of Figure 6.14; simplification is accomplished using both the Visvalingam and Leung–Koehnen algorithms. (Courtesy of National Historical Geographic Information System.)

FURTHER READING

Buttenfield, B. P. l. (1990) "NCGIA Research Initiative 3: Multiple Representations." *http://www.ncgia.ucsb.edu/research/initiatives.html#i3.*

This NCGIA working paper summarizes the results of Initiative 3 on multiple representations held in 1989 and includes a comprehensive bibliography of earlier work on the subject.

Goodchild, M. F., and Quattrochi, D. A. (1997) "Scale, multiscaling, remote sensing, and GIS." In *Scale in Remote Sensing and GIS*, ed. by D. A. Quattrochi and M. F. Goodchild, pp. 1–11. New York: Lewis.

This edited volume explores scale from a variety of perspectives, including spatial and temporal statistical analysis, multiple scaled data for the analysis of biophysical phenomena, and landscape ecology.

Jensen, J. R. (1996) *Introductory Digital Image Processing: A Remote Sensing Perspective*. 2nd ed. Upper Saddle River, NJ: Prentice Hall.

Provides a detailed description of many image processing techniques, including those considered to be part of raster-based generalization.

João, E. M. (1998) *Causes and Consequences of Map Generalization*. Bristol, PA: Taylor and Francis.

Focuses on the quantitative effects of map generalization. The study uses a series of European maps and also provides a methodology for studying the effects of generalization.

McMaster, R. B., and Shea, K. S. (1992) *Generalization in Digital Cartography*. Resource Publications in Geography. Washington, DC: Association of American Geographers.

This monograph reviews the history of generalization, including many of the basic models, and provides details of the fundamental operations.

Sheppard, E., and McMaster, R. B. (eds.) (2004) *Scale and Geographic Inquiry: Nature, Society, and Method*. Oxford: Blackwell.

This edited volume reviews recent research in scale from the human-social, biophysical, and methodological perspectives.

Weibel, R. (1995) *Cartography and Geographic Information Systems* 22, no. 4 (special issue on "Map Generalization").

This special issue contains a series of papers on both the data models for generalization and generalization algorithms. Several of the papers focus on road generalization.

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