# A Natural Principle for the Objective Generalization of Digital Maps

**Zhilin Li and Stan Openshaw**

ABSTRACT. *Generalization is a major research theme in geographic information systems. This paper describes a natural principle for the objective generalization of digital map data and other spatial data. First, the basic concepts related to generalization are reexamined and the key relationships between conventional cartographic generalization and automated digital generalization are discussed. Some of the previous approaches that have been used for generalization are evaluated to provide a context for developing what is termed a natural principle for objective generalization. How the natural principle works is compared with some methods that are currently used for generalization purposes. Finally, some examples of applying this principle to cartographic features are given.*

KEYWORDS: *natural principle, cartographic generalization, digital generalization, objective generalization.*

## Introduction

The task of generalizing digital map data and other classes of spatial data is an important function of a geographic information system (GIS). However, sound and automated generalization procedures that are able to transform the information content of a map and other spatial information from one scale to another do not yet exist (Muller 1989). It is not surprising that the issue of generalization is included in the international GIS research agenda (Abler 1987; Rhind 1988). Moreover, the increasing availability of large digital map databases is reemphasizing the need for automated generalization capabilities in both cartography and, more frequently, basic zoom and display operations.

Generalization is a traditional topic in cartography and has been the subject of considerable research: Perkal (1966), Topfer and Pillewizer (1966), Tobler (1966), Rhind (1973), Steward (1974), Beard (1987), Muller (1987a, 1987b), Weibel (1987), Nickerson (1988), Boutoura (1989), McMaster (1989a, 1989b), and Shea and McMaster (1989). However, in spite of these efforts, much of the fundamental problem of developing an objective approach to generalization still remains unresolved. This paper suggests a possible solution, based on observations of natural phenomena.

## Generalization as a Cartographic Process

It is useful to start by briefly reviewing what is meant by cartographic generalization. This requires some attention to three major topics: (1) the implication of generalization as a cartographic operation; (2) the reasons behind cartographic generalization; and (3) the extent to which digital map generalization resembles the traditional cartographic generalization process. Indeed, only after these aspects have been clarified can analytical algorithms be developed that may solve some of the problems associated with the automated generalization of digital map data.

## Some Implications of Cartographic Generalization

A major problem is determining precisely what cartographers mean by the concept of generalization. Cartographic generalization is an inconsistent process of map data simplification, but not data reduction, that cartographers perform in a subjective but constrained manner. Therefore, cartographic generalization is not a purely scientific process because it involves a highly artistic skill component. As a result, it is difficult for cartographers to specify in any explicit fashion a universal set of rules that might, for instance, be used to build a knowledge-based expert system. Indeed, there is scarcely any consensus as to what cartographic generalization actually means.

Keates (1989, p. 37) offers a useful working description. He writes: "As a map is always at a smaller scale than the phenomena it represents, the information it contains must be restricted by what can be presented graphically at map scale. This adjustment process is referred to as generalization." This implies that cartographic generalization is a process of restricting the nature and amount of information about phenomena that can be represented on a map at a specified scale. It seems that use of the word "restricted" implies that cartographic generalization is a passive process. Therefore, another term, "extracting," might be more appropriate. Thus the term generalization may be loosely redefined as a process of extracting useful information from a database about selected phenomena that are to be represented as a map at a certain scale using a particular output medium. In traditional cartography such a process consists of five operations: (1) selective omission, (2) simplification, (3) combination, (4) exaggeration, and (5) displacement (Keates 1989).

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It needs to be noted that there are also other sets of operations. For example, Shea and McMaster (1989) identified 12 operations as follows: simplification, smoothing, aggregation, amalgamation, merging, collapse, refinement, typification, exaggeration, enhancement, displacement, and classification. In the context of this study, the terminology identified by Keates is followed so that the term "simplification" means that the feature becomes less complex, but the main characteristics of the feature are kept (Keates 1989).

## Reasons Behind Cartographic Generalization

In essence, Keates (1989, p. 38) is suggesting that there are key elements to generalization: scale/graphics requirements and characteristics/importance. The first pair of elements influences legibility and the second pair selects which characteristics are deemed important. He claims that

> The first pair are determining conditions; the difference in scale between the map and real world phenomena, or the derived map and the source map, controls the available space, in which there are minimum requirements for graphic legibility. The effects of scale ratio, space and dimensions are in many respects measurable factors.The second pair are essentially judgments; they reflect the need to retain the essential characteristics (in terms of shape and configuration) of the phenomena represented, and also the fact that some things are judged to be more important than others, both within the same general class, and between classes. Therefore, some things will be retained, and exaggerated if necessary, and may be emphasized within the map design.

These statements imply that cartographic generalization is applied for the following reasons:

1. Limitations on the available space on the output media to represent all the information that exists
2. To ensure adequate clarity for graphic presentation
3. The assumed restricted interest of the human viewer to only certain aspects of natural phenomena and to certain degrees of detail

## Some Key Characteristics of Cartographic Generalization

As a consequence of cartographic generalization, the map model representing reality is adjusted and modified in an ad hoc and subjective manner. Unlike a mathematical optimization problem, there is no objective function but a series of intuitive and artistic guesses as to the most appropriate model parameters. The smaller the map scale, the larger the degree of adjustment or modification that is needed and the greater the potential errors and misrepresentation that is involved.

João et al (1990) clearly illustrate the consequences of generalization on the representation of a town displayed at different map scales. At a 1:1,250 scale map, the layout of individual buildings and plots, including fences, can be clearly seen. At the 1:10,560 scale map, the buildings are represented by areas but the finer details are now lost. At the 1:50,000 scale, however, only groups of buildings joined to form contiguously built-up urban regions can be seen. At 1:250,000 scale, the entire town is represented by a single area polygon. Finally, at 1:625,000 scale, the whole town is represented by a single point. That is to say, the main characteristics of generalization are that, after the application of a scale-driven generalization process to a larger scale map, the features on the smaller scale maps are more abstract and symbolic.

Indeed, Imhof (1982, p. 86) has provided a more precise description of characteristics of cartographic generalization as keeping "the greatest possible clarity of meaning and good legibility, simplicity and clarity of graphic expression; clear expression of metric information; and good characterization in the forms." However, at the same time, an attempt is also made by cartographers to keep "the greatest possible accuracy, with respect to the scale of the map; the most naturalistic forms and colors" since all these together make "a beauty peculiar to the map itself" (1982, p. 86).

## Some Aspects of Digital Map Generalization

So far, attention has been restricted to the conventional cartographic generalization process. The purpose of this discussion was to develop a better understanding of the implications of map generalization to see what might be implemented using analytical methods to perform an automated generalization of digital map data. In digital map generalization, the operations need to be carried out by analytical methods that operate (ideally) in a completely automated fashion. The difficulty is that the subjective operations need to be carried out by analytical algorithms that incorporate either rules or objective criteria. Therefore, the critical question is what kind of criteria or rules should be incorporated.

As has been discussed previously, a conventional cartographic generalization process includes two major components: one component is related to an objective operation and a second component to an essentially subjective and artistic operation. The scale and graphic aspects of generalization constitute relatively objective criteria. However, the other features relating to characteristics and importance are largely dependent on personal judgment influenced by purpose, and thus constitute subjective criteria. Unfortunately, in cartographic practice, these two criteria are integrated together in the operator's mind while he or she is carrying out generalization operations, so that the whole process of cartographic generalization seems totally subjective to an outsider. Another point that needs to be emphasized is that human generalization is based on the operator's experience and draws upon an impression of those features within the area of interest that are considered or perceived to be important for a given purpose.

It may seem that some kind of knowledge-based system is needed to carry out such a subjective process, although this does require that the relevant "rules" can be written down. Another possibility would be a supervised neural net that could be "trained" by cartographers to perform generalization functions. However, both approaches assume that the objective is to automate and replicate the skills of the manual cartographer for subsequent use in computer systems and, accordingly, that such a system could at best never outperform its human instructor. This objective might be questioned. The argument is that it might be possible to make the generalization process more consistent, more objective, and thus more scientific with the assistance of the computer, but only if appropriate rules or criteria are employed. It is, therefore, urgent to set out such rules or criteria if they exist.

## Previous Efforts on Digital Cartographic Generalization

Numerous papers have been written on digital generalization. A comprehensive review of previous work has been made by Brassel and Weibel (1988). Additionally, Shea and McMaster (1989) offered a comprehensive framework. However, in the context of digital generalization, most of the effort has focused on line generalization. A comprehensive review of these efforts was made by McMaster in 1987. Many investigators have contributed to this topic: Perkal (1966), Peuker (1975), McMaster (1986), Muller (1987a, 1987b), Thapa (1988), Boutoura (1989), Buttenfield (1989), Carstensen (1989), Jenks (1989), McMaster (1989b), and Monmonier (1989).

From the literature on line generalization, it can be found that most of the investigators try to select a certain number of points that are regarded as being important in line representation. These selected points are then used to represent the original line and the new line is viewed as being simplified or generalized. These are, in fact, methods for the removal of data redundancy in a digital data set (i.e., data reduction). However, generalization and data reduction are not the same, although some kind of generalization effect may be created by the reduction of coordinate pairs. Also, the parameters of these techniques are difficult to relate to changes in map scale. To make things worse, these techniques may even create undesirable spatial conflicts (Muller 1990). Therefore, the use of a data reduction technique as a generalization procedure can be misleading.

Another technique that has been used in line generalization is smoothing using either a mathematical approximation technique or a low-pass filter such as a moving average or epsilon filter (McMaster 1989b). Smoothing methods try to filter out the high-frequency parts of spatial variation using such techniques as a convolution operation, where the widely used weighted-moving average is simply a discrete convolution. Such techniques are controlled by the weights and the number of points to be taken into consideration, and again, these parameters are not easily related to scale change. More importantly, these techniques are also not likely to remove the undesirable spikes. Therefore, smoothing methods may also have difficulty in producing desirable results for generalization purposes. McMaster (1989b) has suggested a more promising method (i.e., using a point reduction algorithm in conjunction with a smoothing procedure). Further research is desirable to see what kind of potential benefits one could gain by using such a hybrid method.

## Generalization as a Spatial Analysis Function

Generalization should also be regarded as a data model creation process for the analysis of spatial data. An analogous generalization process occurs when data displayed for a small set of areal units are aggregated to increasingly larger areas. There is a loss of detail and a series of fundamental changes occur in the nature and characteristics of the areal objects being displayed. The generalization process of spatial aggregation has created spatial patterns that were not evident in the original data and changed or destroyed others that were. Traditionally, this too has been a cartographic process, although experiments in manipulating the scale and aggregation processes to optimize various arbitrary objective functions have been attempted (Openshaw 1978, 1984). The problem becomes one of determining which objective function to use. One possibility is to seek to minimize deviations from large scale detail when scale is reduced. At the same time, it is interesting to note that spatial analysts, such as Batty et al. (1989), have sometimes sought results similar to the objectives of cartographic generalization as set out by Imhof (1982).

## A Natural Principle for Objective Generalization

A key question to be asked is whether it is possible to develop a more objective approach to generalization. The idea developed here is to mimic the principle by which nature performs this process. It has been suggested that one of the reasons for cartographic generalization is the link between map scale and graphic legibility. That is to say, when the scale is reduced, the space for legends and map detail becomes smaller. Therefore, generalization needs to be applied to retain clarity on the map display and reduce clutter that would otherwise totally fill the map space with unrecognizable detail. This space reduction is due to scale reduction and the process provides an obvious and objective criterion that can be used in analytical algorithms to automate the generalization process. In essence, the same paradigm can be applied to other types of spatial data. The remaining problem is to determine how the scale change can best be linked to the degree of generalization needed to retain legibility.

## Examples Illustrating the Principle

Initially, some simple examples will be given to serve as an introduction to what is a natural principle for objective generalization. When a person is nearer an object, he or she can see more detail. When one gets further away from the object, less detailed information can be seen. In this case, it can be said that the image of this object in one's mind is becoming more generalized. Such a phenomenon is, of course, a process of objective generalization, as produced by nature.

A good example of this kind of generalization is the earth's surface viewed from a distance. If the earth is viewed from an infinite distance, it should appear to be a point. If it is viewed from the moon, it can appear like a blue ball. In this case, the earth's surface is so generalized that detailed information on the spatial variation is totally lost. This could be regarded as the highest degree of generalization yet managed by man. When the earth's surface is viewed from a satellite, the spatial variation becomes extractable, but it is still very generalized. The amount of detail depends on

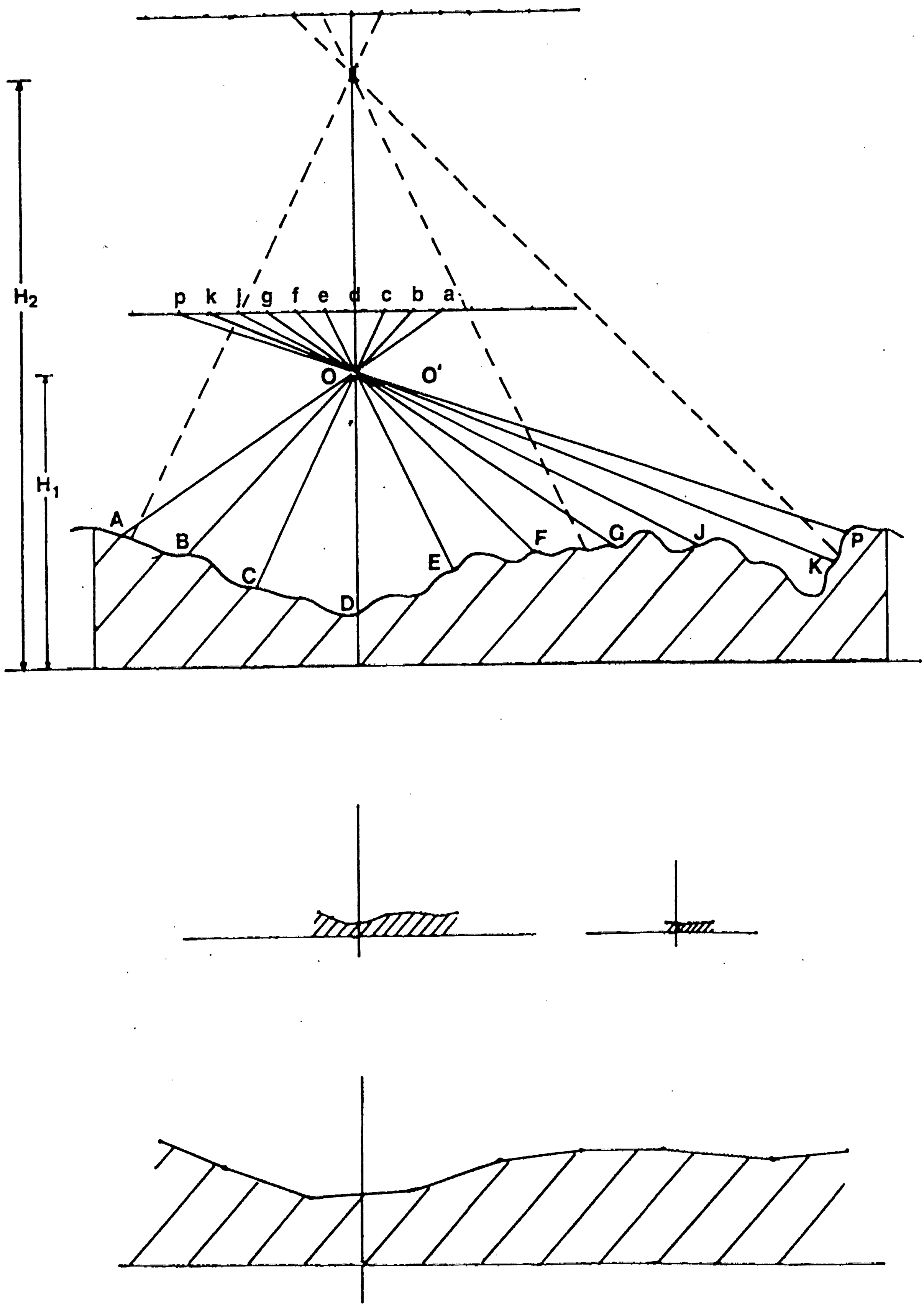


**Figure 1.** *Illustrating the natural principle in three-dimensional data. (a, top) Sectional view of the generalization of a three-dimensional surface. (b, middle left) Generalized results due to five times scale reduction. (c, middle right) Generalized results due to 10 times scale reduction. (d, bottom) Figure 1b plotted at the same scale as Figure 1a.*

.e resolving power of the sensors used to view it. When .e earth's surface is viewed from an airplane, much more ›tail can be seen. This is the world of the photogrammetrists.

On the other hand, surveyors have observed that it is .fficult to determine the positions of characteristic points ı the terrain surface unless they are viewed from a dis- .nce. By viewing the terrain surface from a distance, some .nd of generalization has been applied so that the main :atures (e.g., the characteristic points) are extracted from ıe detail so that the key characteristic points are distin- uishable from the rest. Another example could be the sur- ıce of a highway from different distances. It appears rough it is viewed up close or with magnification. However, it ppears smooth if it is viewed from a distance. Again, this ; a result of a natural generalization process.

## The Natural Principle and a Corollary

n the previous examples, the generalization effect is cre- .ted by the limitation of the human eye's resolution or the imitation of the resolving power of the imaging system. In hese cases, the information about the spatial variation of he terrain surface or road surface beyond the size that can ›e identified by human eyes or the imaging system is lost. Гhese phenomena imply that for a given scale of interest, ıll details about the spatial variation of geographical objects beyond certain physical limitations are unable to be presented and can be neglected. This underlies the principle by which nature operates the generalization process. This limitation may be called the fuzzy element, which is indeed the smallest visible object.

It follows, therefore, that a simple corollary to this process can be used as a basis by which objective generalization algorithms can be implemented: by using a criterion similar to the limitation of the human eye's resolution, and neglecting all the information about the spatial variation of geographical objects beyond this limitation, some generalization effect similar to those seen in the previous examples can be obtained. This critical quantity, termed here the fuzzy element, may be approximated by a small circle, small raster, or any other geometric entity. Therefore, this natural principle can be implemented in various ways, but the resulting products should be similar. It is hardly novel, but it is truly universal and fundamental to the generalization issue in GIS.

## Illustrating the Natural Principle in Three-Dimensional Variation

Figure 1a illustrates the presence of generalization in three-dimensional spatial variation based on this corollary. It is a sectional diagram of the generalization viewed from point

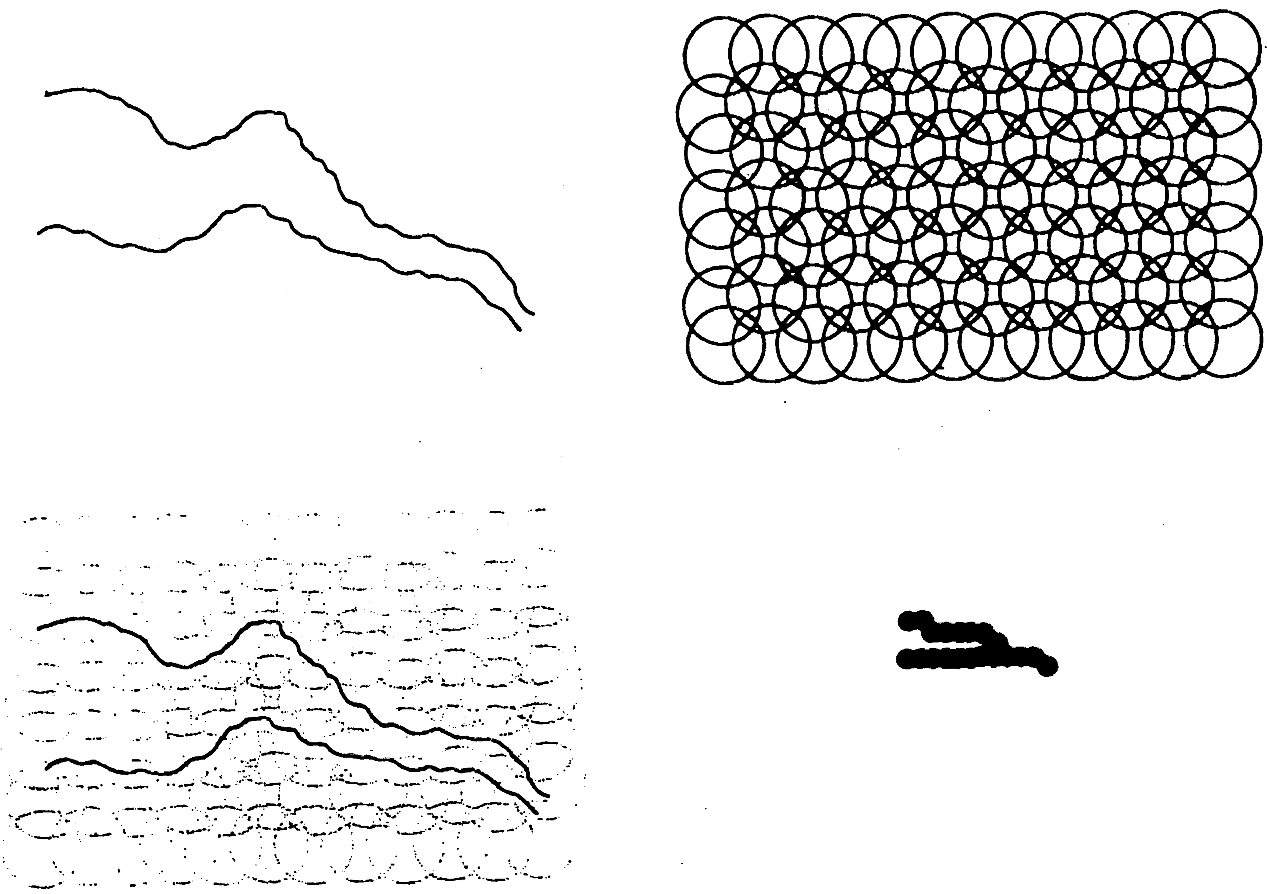

Figure 2. *Illustrating the natural principle in two-dimensional data. (a, top left) A river presented by double lines to be generalized. (b, top right) A set of (enlarged) overlapping fuzzy circles. (c, bottom left) Superimposition of (a) and (b). (d, bottom right) Result generalized from (a), each dot represents the corresponding fuzzy circle in (c).*

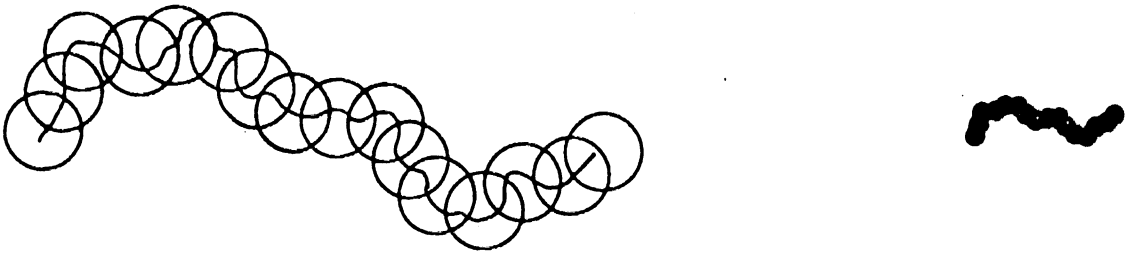

Figure 3. *Illustrating the natural principle in one-dimensional data. (a, left) A line to be generalized and a set of fuzzy circles drawn on it; all spatial variation within fuzzy circles can be neglected. (b, right) The result generalized from (a), each dot represents the corresponding fuzzy circle in (a).*

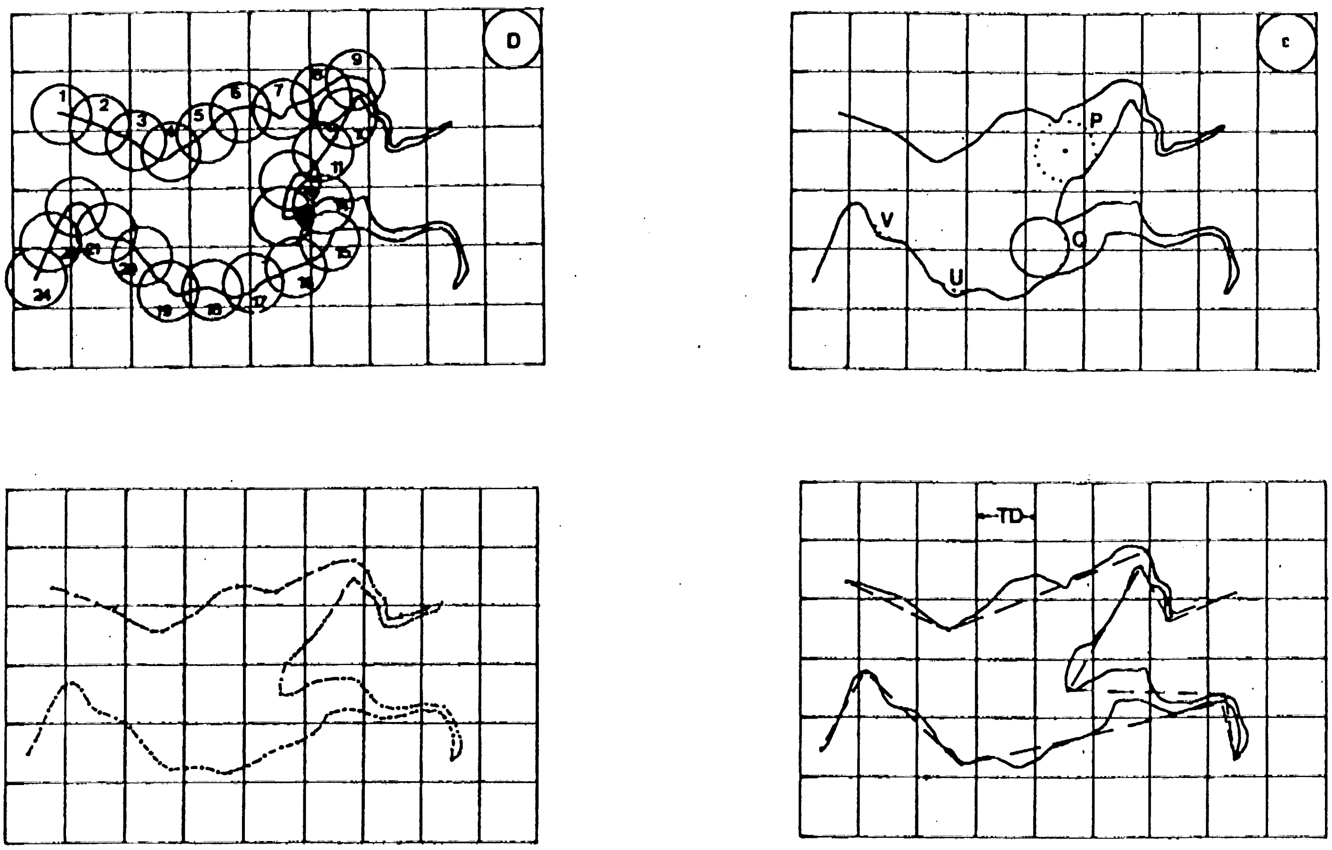


Figure 4. *Generalizing a coastline by various methods. (a, top left) By the natural principle (the raster-vector algorithm). (b, top right) By ϵ-circle. (c, bottom left) By five point weighted moving averaging. (d, bottom right) By retaining critical points (the Douglas algorithm).*

O. The height of point O from the datum is represented by $H_1$, which is five times the distance Od; therefore, the generalized model is about five times reduced, varying from point to point. The distances between ab, bc, ..., and pk are equal, which represents the diameters of the contiguous fuzzy circles projected onto the image plane. The projection of these fuzzy circles with diameter ab, bc, ..., and pk onto the object space represents the spatial variation between points A and B, B and C, ..., and P and K. According to the natural principle of generalization, all detail within the fuzzy circles ab, bc, and pk is totally lost. Therefore, after such a scale reduction, the spatial variation between points A and B, B and C, ..., and P and K cannot be retained. By neglecting the spatial variations between points A and B, B and C, ..., and P and K, the desired objective generalization can be achieved. Neglecting the spatial variation between any two points is achieved by using the average value of the two end points to represent this variation. For example, a point with the average coordinates of points A and B is representative of the spatial variation between points A and B.

Figure 1b is the generalized model of the spatial variation shown in Figure 1a with a scale reduction of five times. Figure 1c is also a generalized model of the same spatial variation but with a scale reduction of 10 times. Figure 1d is the five-times enlarged spatial variation of Figure 1b. In Figure 1d much detailed information about the spatial variation shown in Figure 1a is lost, although it is plotted at the same scale as Figure 1a.

However, it needs to be noted that with this method the

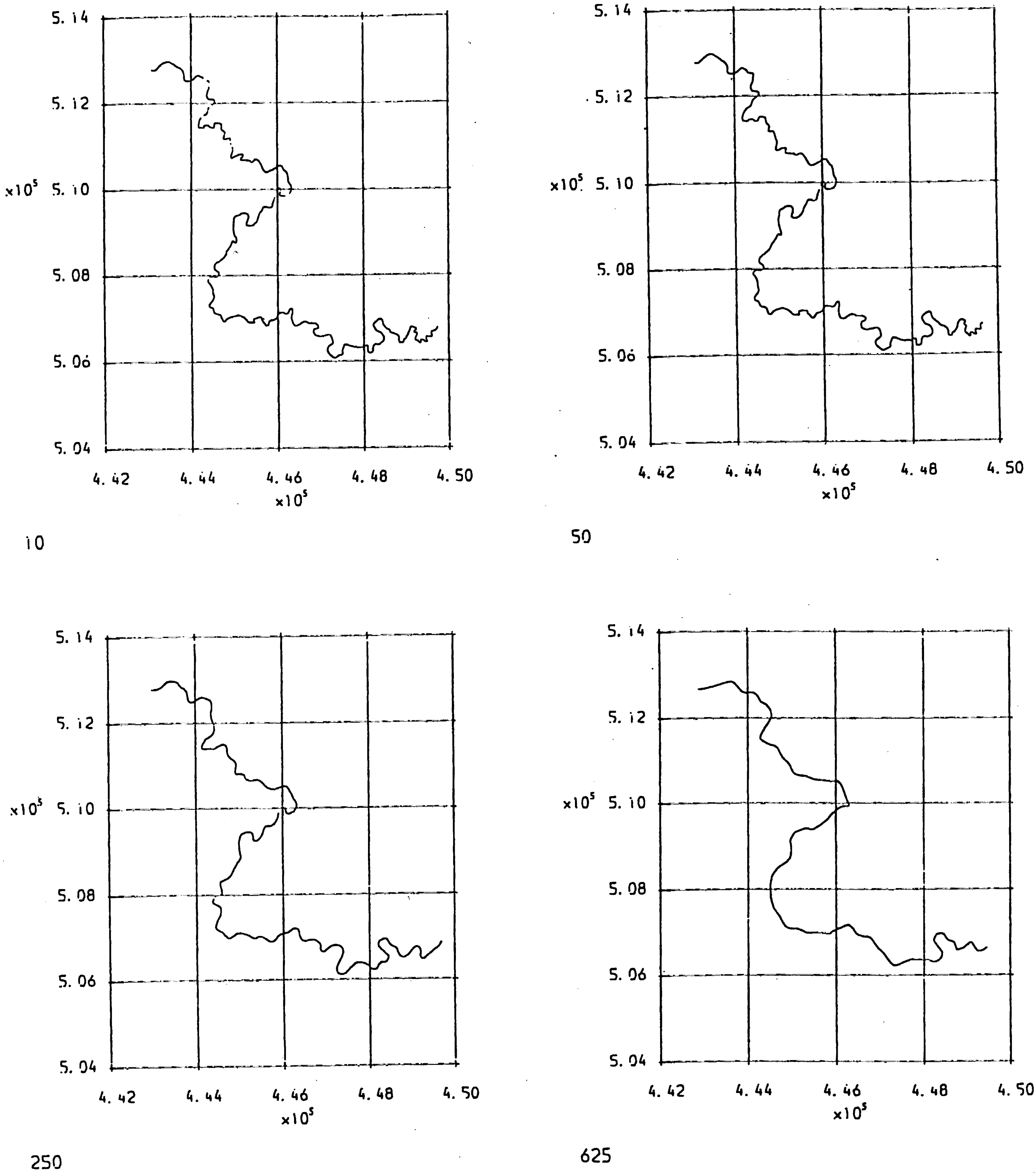


**Figure 5.** *A river feature digitized from four different scale maps. (a, top left) From 1:10,000 scale. (b, top right) From 1:50,000 scale. (c, bottom left) From 1:250,000 scale. (d, bottom right) From 1:625,000 scale.*

degree of generalization could vary from point to point depending on the height of points. The closer a feature is to the viewpoint, the less generalization will occur. Part of this problem can be solved by systematically moving the viewpoint and generalizing only a piece of the surface from each position. For example, the piece around point D can be generalized from the viewpoint O, but the piece around point E might be better generalized with viewpoint O′. In this example, no overlap between two successive fuzzy circles was considered. However, in practice this would be desirable.

## Illustrating the Natural Principle in Planimetric Data

In this section, attention is paid to the generalization of two-dimensional and one-dimensional data. First, consider

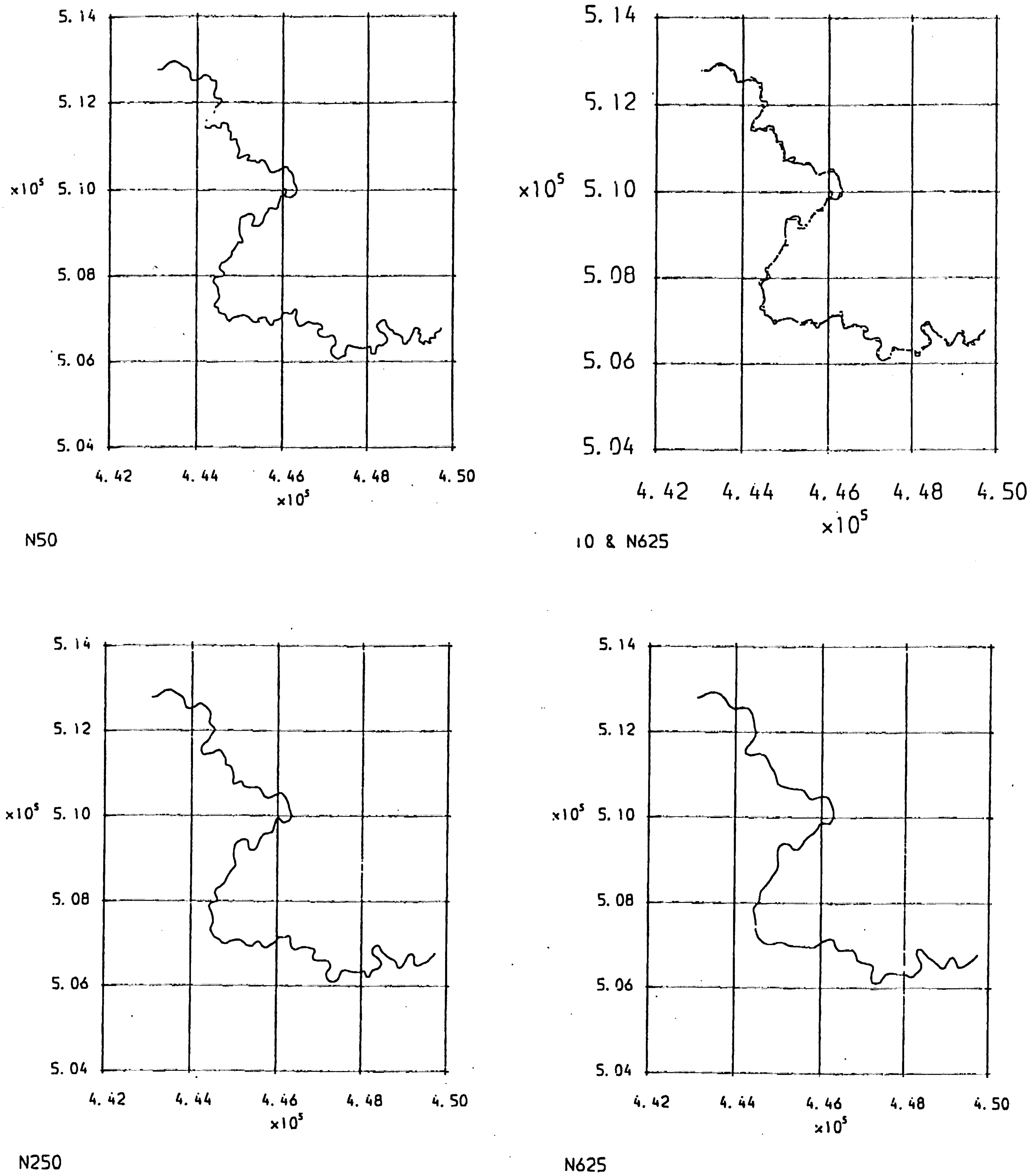


**Figure 6.** *The river feature (Figure 5a) at 1:10,000 generalized by the natural principle to various scales. (a, top left) Generalized result at 1:50,000 scale. (b, top right) Superimposition of original feature with the generalized result at 1:625,000 scale. (c, bottom left) Generalized result at 1:250,000 scale. (d, bottom right) Generalized result at 1:625,000 scale.*

the generalization of two-dimensional data (Figure 2). Figure 2a represents a river segment from a larger scale map, drawn with double lines. This can be considered an area feature and is to be generalized with a scale reduction of four times. Figure 2b shows the overlapped fuzzy circles on the smaller scale map, but enlarged and plotted at the same scale as Figure 2a. The superimposition of Figure 2a onto Figure 2b is shown in Figure 2c. Again, the spatial variation within a fuzzy circle is neglected. In doing so the results in Figure 2d can be obtained. This represents a version of the river as generalized by this natural principle with four-times scale reduction. The river at the right side

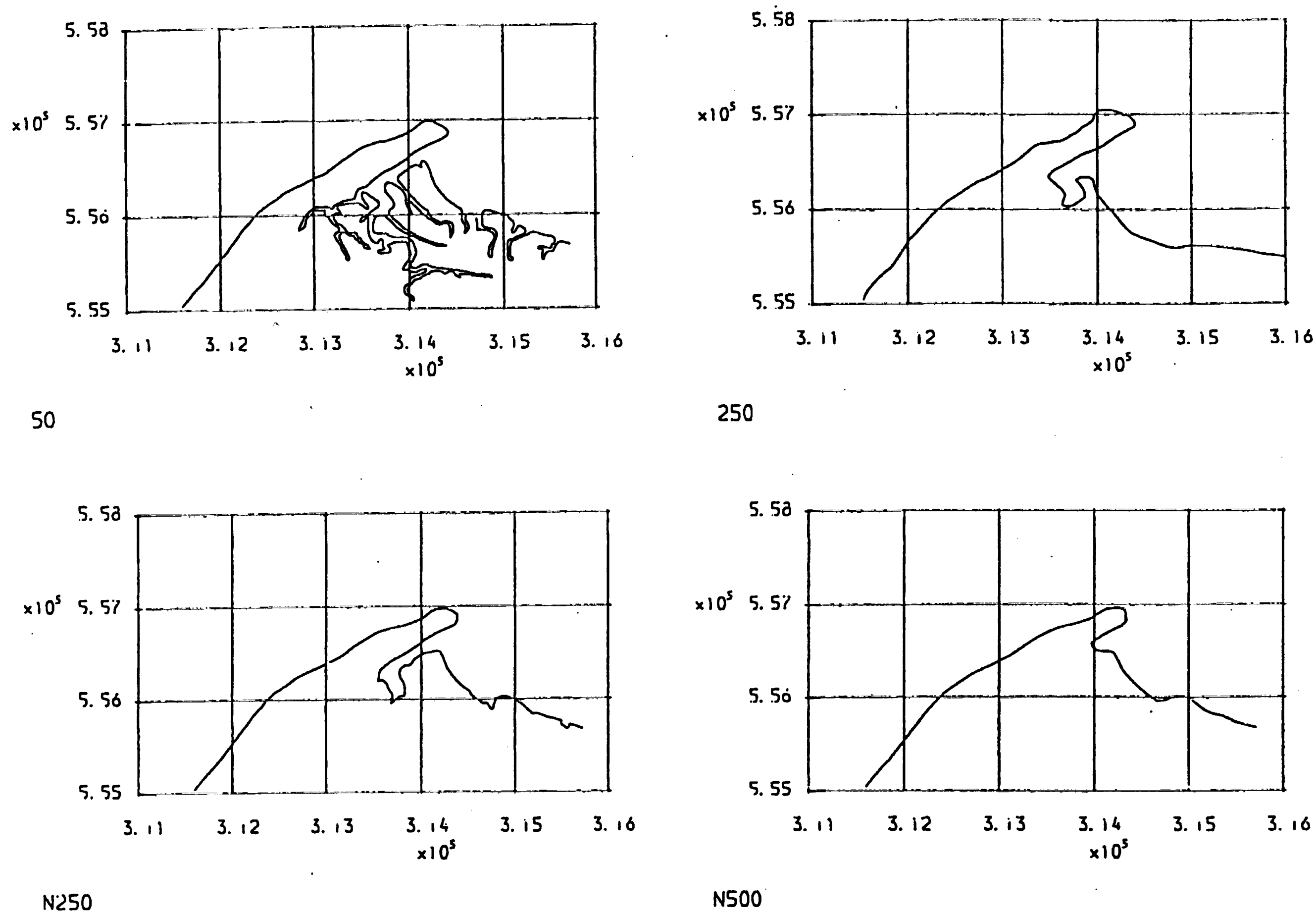


Figure 7. *Generalization of a coastline. (a, top left) A coastline on 1:50,000 scale map (original feature). (b, top right) The same coastline on 1:250,000 scale map. (c, bottom left) Result generalized by this principle to 1:250,000 scale. (d, bottom right) Result generalized by this principle to 1:500,000 scale.*

of Figure 2d cannot be drawn with double lines anymore, given this level of scale reduction, and is now represented by a single line.

Consider next the generalization of one-dimensional data (Figure 3a). The curve line represents the feature (e.g., river) to be generalized and, along this line, a set of overlapping fuzzy circles are drawn. Assuming that all the spatial variation within these fuzzy circles is removed, the result, shown in Figure 3b, is for a scale reduction of four times.

## Implementing the Natural Principle

The discussions conducted in the previous sections are theoretical. Indeed, this paper is intended to merely offer and illustrate a new theoretical basis for objective generalization. As one can imagine, this general principle can be implemented in various ways. For example, the authors have implemented one set of new algorithms for generalizing line features based on this natural principle in both vector and raster modes, and also a raster-vector hybrid (Li and Openshaw 1990).

One important task in algorithm implementation is to determine the size of the parameter representing the diameter of the fuzzy circle for different map scales. The following might be considered as key parameters: (1) the width of plotting pen nib and/or output media resolution; (2) the tolerable planimetric accuracy of the input maps; and (3) various empirical values related to map perception by users.

When plotting a map, it is a common practice to request that a line should be plotted by a pen with a certain width, say W. If the separation between two lines is smaller than W, these two lines will be too close to be distinguished as separate lines. Therefore, the values of the criteria, denoted as D(S), can be expressed as follows:

$$D(S) = f(W, Si, So) \qquad (1)$$

where, Si and So are the scale factors of the input and output maps, respectively. Additionally, the tolerable planimetric accuracy given in a map specification may also be used to determine the values of the fuzzy element. The values for D(S) may also be determined by trial-and-error experimentation. A more detailed discussion of this specific topic lies outside the scope of this paper.

Another important aspect is the extent of the overlap between the so-called fuzzy elements (Figure 2, Figure 3, and Figure 4a). Indeed, the concept of overlap is an analogue to nature and thus is an inherent part of this natural principle. In practical terms, the introduction of overlap can serve two purposes: (1) it reduces the dependency of generalized results on the position where the generalization process is started and (2) it helps in preserving some of the spatial variation of the original features. Clearly, it is useful but it does raise questions related to how much is the desirable amount and how to implement it in practice. The first question is still under investigation, but the experience so far suggests that it is not critical and a value of 20% works well.

Overlap can be implemented in two ways (i.e., either by using a predesigned template (Figure 2) or by moving a fuzzy element along the most approximate directions of the feature (Figure 3). Consider the latter with a fuzzy raster cell as an example. From a given position, there are eight possible directions for the movement of the raster cell (i.e., up, down, left, right, upper left, upper right, lower left, and lower right). The most approximate direction for such movement could be determined by considering the point positions of the feature. In this way, a string of raster cells similar to Figure 3a or Figure 4a could be identified and the feature generalized.

## A Comparison with Existing Methods

To clarify how this natural principle works, it seems appropriate to offer a brief comparison with some of the existing methods that have been used for generalization. The following methods are examined: the filtering technique using a weighted moving average (Tobler 1966), the $\epsilon$-generalization of Perkal (1966), and the popular critical point selection for data reduction (Douglas and Peucker 1973). To illustrate the differences, a linear feature (with considerable complexity) was selected. Figures 4a through 4d display the results produced by these four different methods.

Figure 4a shows the generalization of this line by the natural principle. In this case, a set of overlapping fuzzy circles with diameter D (labeled 1 to 24) are drawn along the line according to certain rules (Li and Openshaw 1990). The line joining the centers of these fuzzy circles represents the generalized version of this feature. The two spikes are removed since they can no longer be represented, given the value of the fuzzy circle used here. Figure 4b shows the results of the $\epsilon$-generalization procedure using a circle with a diameter the same size as the fuzzy circle. The spikes (area P and Q) are removed, but the rest of the line remains unchanged except for a slight change near U and V. Figure 4c is the result produced by applying the five point moving average method used by Tobler (1966). The following weights are used: 0.1, 0.2, 0.4, 0.2, and 0.1.

By comparing Figure 4c with Figure 4b, it can be seen that only little modification was made. It is impossible with this technique to remove the undesirable spikes. Figure 4d is the result produced by the Douglas algorithm. Again, the tolerance distance is selected to be the same as the diameter of the fuzzy circle (or $\epsilon$-circle), and the result is different from that produced by the natural principle. The latter seems more logical, although it remains to be tested how similar the results are to those obtained by manual cartography.

## Application of the Natural Principle to Practical Data

The natural principle was also applied to generalize more realistic cartographic features. A river and a coastline were digitized from topographic maps of various scales and compared with the result of generalization according to this natural principle.

Figure 5 shows a river digitized at four different map scales (1:10,000, 1:50,000, 1:250,000, and 1:625,000). From Figures 5a through 5d, this feature becomes simplified in a natural way with the decrease in map scale. The natural principle is applied to this feature at a scale of 1:10,000 and a set of generalized results at corresponding scales are shown in Figure 6. By comparing Figure 6 with Figure 5, it can be seen that the generalized results are similar to those produced by the manual process. Figure 6b is the superimposition of the generalized result at 1:625,000 onto the original feature (1:10,000 scale), which shows the faithfulness of the generalized result to its original form.

The strength of this natural principle is its universality, so it should also be capable of coping with more complex features and other types of data. The former can be demonstrated by applying it to a complex coastline. Figures 7a and 7b show the same feature on 1:50,000 scale and 1:250,000 scale maps, respectively. Figure 7c is generalized according to the natural principle from the 1:50,000 scale to 1:250,000 scale, while Figure 7d is the result generalized from Figure 7c. Note that it is similar to Figure 7b. Also, this coastline on 1:625,000 scale maps is similar to that shown in Figure 7(d). In these examples, the raster-vector mode algorithm (Li and Openshaw 1990) was used and a 20% overlap between two successive fuzzy rasters was applied.

In addition to its consistency, the generalized result has the following characteristics: (1) the original feature is smoothed and simplified, but it is still very natural; (2) any undesirable spikes are removed if they cannot be presented at a given map scale; and (3) the main characteristics of the original feature are retained with clarity and faithfulness to the original form. Indeed, this is exactly what should be done by a generalization procedure. These examples, although still limited, show the feasibility and potential of utilizing this natural principle as a universal rule for the purpose of generalizing digital map data.

## Discussion

A natural principle for digital map generalization is described that provides the basis for an objective approach to the problem of automating generalization. This principle is based on naturally occurring generalization phenomena. It should be applicable at least to the curved lines of natural phenomena as well as to power lines, coastlines, and contour lines. Additionally, the principle might also be applied to other complete geographic entities, providing the basis for determining what features from a large scale map should be seen on a small scale map displayed on a particular output device. The principle is self-evident, at least to non-cartographers. Indeed, the main difficulty in trying to solve the generalization problem in cartography might appear to have been too much knowledge of manual cartography! The method demonstrated here also reminds the GIS user of the facts of digital mapping and the limitations of the cartographers' map model of reality. It should now be possible, from a large scale source, to draw maps at a small scale that only show what might reasonably be seen: a kind of digital map equivalent to the aerial photograph or satellite image. Of course, some kind of subjective exaggeration of certain related features may still be desirable. For example, the user may wish to view certain features and accept the scale exaggeration that this entails. This selection should, however, be user-controlled and dynamic, rather than fixed by some anonymous cartographer who is probably long since dead.

This article has concentrated on theoretical aspects. Subsequent work will describe, in greater detail, implementation with algorithms for both vector- and raster-mode generalization, as well as a hybrid vector-raster method. The next stage will also involve the application of this natural principle to various types of digital map data sets. Of particular importance is the growing belief, at least by the authors, that it should now be possible to obtain a reasonably intelligent, universally applicable generalization procedure that will operate with any and all kinds of geographic information by switching to a raster representation and applying the objective principle at the pixel level.

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