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Algorithms for automated line generalization[1] based on a natural principle of objective generalization

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Abstract. This article describes a new set of algorithms for locally-adaptive line generalization based on the so-called natural principle of objective generalization. The drawbacks of existing methods of line generalization are briefly discussed and the algorithms described. The performance of these new methods is compared with benchmarks based on both manual cartographic procedures and a standard method found in many geographical information systems.

1. Introduction

The generalization[1] of line features is an important process whenever there is a change of map scale or data sets from different scales of source document are mixed together. The problem of generalization occurs in both traditional cartography and in many applications of geographical information systems (GIS). It is not purely a cartographic problem but an issue that also affects the computer display of maps as well as their manipulation and storage in GIS environments. There is, therefore, an increasingly urgent need to develop fast, efficient and sensible procedures for map generalization that can be performed by a computer in an automated fashion under the control of an algorithm. Such algorithms should either attempt to mimic the manual cartographic process or else seek to improve upon it. Although a considerable research effort has already been invested in automating various aspects of the process of generalizing digital maps, there still remain some basic problems to be solved. Indeed, currently there are no entirely satisfactory general-purpose solutions to the problem. Given the importance of this basic task, it is hardly surprising that this problem is included on the international GIS research agenda (see Marble 1984, Abler 1987, and Rhind 1988).

Line generalization is important for a number of reasons. Firstly, it is the most basic of all processes of generalization. Secondly, it has become the traditional starting point for any new study of problems of map generalization. Thirdly, the generalization of physical line features (e.g. rivers and coastlines) is a common problem in GIS. Fourthly, it is regarded as the first hurdle that needs to be resolved in the development of more comprehensive procedures for map generalization (Keates 1989). Finally, it is

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[1] The term 'generalization' has never been clearly defined (Keates 1989). Different terminologies are used by different authors with no standardization. According to Keates (1989) and Visvalingham and Whyatt (1990), the term 'line generalization' used in this article is better replaced by 'line simplification'. This was also suggested by one of the referees. However, McMaster (1992, personal communication) insists that this term is reserved to mean the reduction of line coordinate data as established in existing literatures (see Shea and McMaster 1989). The situation is so confusing that the authors prefer to use the broad term 'line generalization'.

becoming increasingly obvious that the available procedures do not yield satisfactory geometrical results (see, for example, Muller 1990 and Visvalingham and Whyatt 1990).

At the same time the increased availability of digital map databases, such as the Bartholemew's 1 : 250000 data for Great Britain, is likely to increase greatly the need for GIS users to have access to sensible and widely-applicable generalization procedures.

This article outlines a possible solution based on a new approach to the problem. § 2 examines briefly a number of existing methods in order to see what drawbacks they have so that any relevant lessons might be discovered and performance benchmarks established. In § 3 the application of a new approach on the natural principle of objective generalization of Li and Openshaw (1990 a) is briefly described. § 4 gives full details of three algorithms that operationalize this method, together with some empirical results. A comparison of the results produced by the new algorithms with those produced by manual generalization and the Douglas method of data reduction is provided in § 5. Finally, § 6 contains a short discussion of the results and some suggestions for further research.

2. Some remarks about existing methods

It is observed that currently there are many methods which seem to be suitable for line generalization. A recent review paper by McMaster (1987) in *Cartographica* ran to 40 pages with more than 60 papers cited as references. New methods are still being proposed, for example, that by Boutoura (1989). Here, no attempt is made to review the available methods and attention is restricted to making general comments with a view to obtaining useful pointers as how best to develop improved methods.

2.1. *Typologies of methods*

It is worth noting that most available methods used for purposes of generalization are concerned with data reduction rather than generalization. They have been classified in various ways (see, for example, Douglas and Peucker 1973 and Zoraster *et al.* 1984). McMaster (1987) classified these methods into five groups according to the geometrical nature of their computation: (1) independent point routines; (2) localized processing routines; (3) extended local processing routines; (4) external local processing routines; and (5) global routines. On the other hand, Douglas and Peucker (1973) put the existing methods into only three groups: (1) those based on the elimination of points along a line; (2) those based on the approximation of a line using mathematical functions; and (3) those which delete specific cartographical features. This typology may be further simplified into two main types: (1) data reduction methods, and (2) smoothing methods. In practice, methods from the first type are the more widely used. An evaluation of one typical example from this group is presented later to demonstrate their shortcomings.

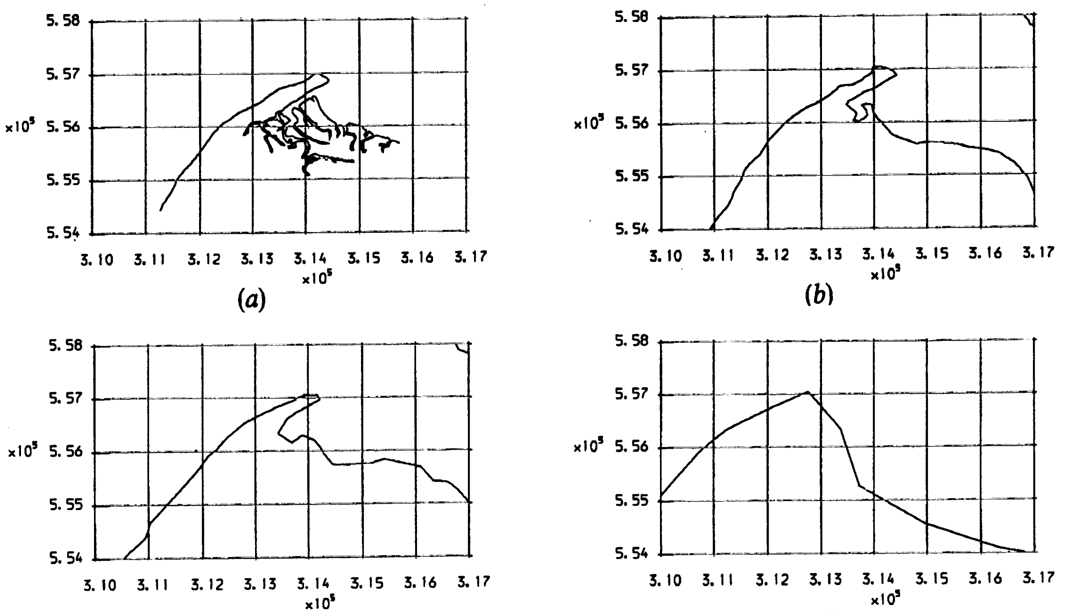
2.2. *Some problems with data reduction methods*

From a general methodological viewpoint, there are two quite different approaches, depending on the basis upon which methods are developed. One of them may be termed the problem-based or map feature specific approach; the other may be referred to as a map feature independent approach based on some theory of the generalization process. In the former, essentially *ad hoc* methods, the starting point is a particular instance of the generalization problem. Methods are then developed to try and solve this problem. Such methods are inevitably highly subjective and are problem specific.

The existing methods for automated line generalization all belong to this category. They are problem-specific because they are applicable only to line features.

It is further noted that many of the existing methods that use a strategy of data reduction are based on the concept of critical points, an idea that was introduced by Attneave (1954) to describe the skeleton of a cat. The classic example of this type of methods is the Douglas data reduction algorithm (Douglas and Peucker 1973), which is now widely regarded as a standard routine for line generalization both in text books (e.g., Monmonier 1982) and in many GIS packages (e.g., Arc/Info GENERALIZE command). Yet a recent evaluation by Visvalingham and Whyatt (1990) reveals that there are many problems with this method from both theoretical and practical points of view. For example, they found that the so-called critical points are not always critical and that there is a lack of consensus in over half the points selected by this method in comparison with manually-selected significant points. Perhaps a more serious drawback associated with these methods concerns a major difference in functioning compared with the process of manual generalization. The latter tends to preserve the shape of the main features of a line but the Douglas algorithm, for instance, may also pick up many points which describe only minor features. As a result, some researchers, such as Monmonier (1986) and Thapa (1988), have argued that this method may be used only when changes of scale are small.

It is useful at this point to consider an empirical example to demonstrate some these shortcomings and also the importance of developing new algorithms for line generalization. Figure 1 shows four versions of a fairly complex segment of coastline digitized from maps at different scales. This segment has been manually digitized from the Ordnance Survey's topographic maps of Great Britain at four different scales. The digitization was performed very carefully to keep coordinate errors and eye/hand generalization to a minimum. In general as expected, the shape of this line becomes



(a) (b)

(c) (d)

Figure 1. A piece of coast line on different scale maps (coordinates are in metres). (*a*) On 1:50 000 scale map; (*b*) on 1:250 000 scale map; (*c*) on 1:625 000 scale map; (*d*) on about 1:3 500 000 scale map.

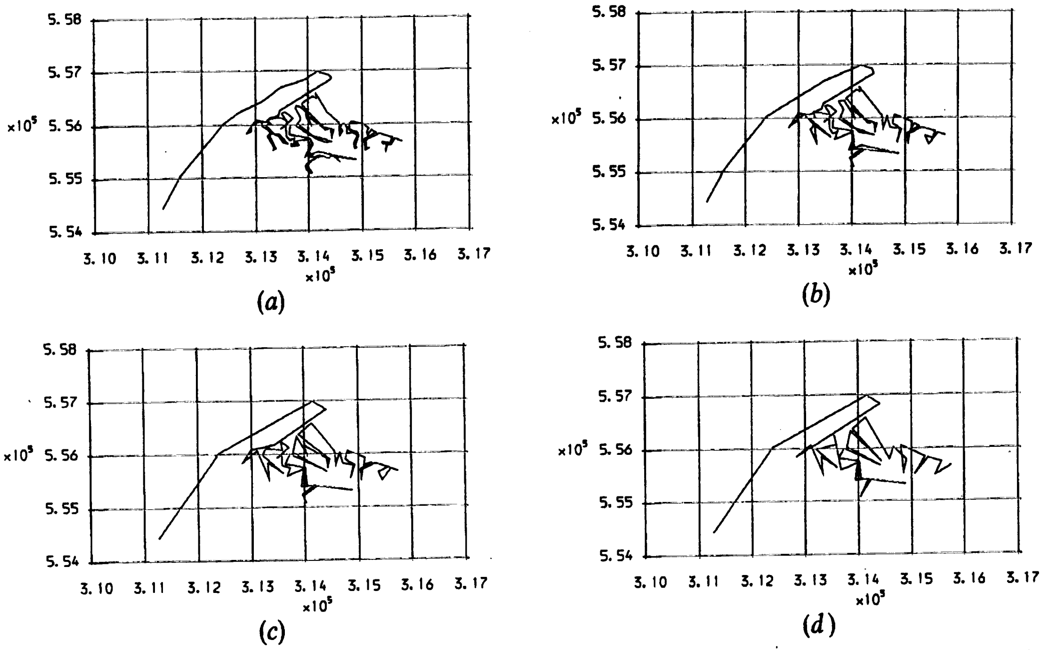


Figure 2. Generalization of the coast line by the Douglas data reduction algorithm with different tolerable distances (coordinates are in metres). (*a*) 30 m; (*b*) 60 m; (*c*) 100 m; (*d*) 150 m.

simpler and more generalized with each decrease in map scale. If figure 1 is compared with the results of the Douglas data reduction method in figure 2, it is obvious that no 'equivalently good' generalization of the same coastline segment has been obtained[2].

Of course, this is by no means the fault of the algorithm itself. Indeed, Douglas and Peucker (1973) clearly stated in their original article that this algorithm is 'for the reduction of the number of points required to represent a digitized (i.e., digital) line or its caricature' (p. 122). So it can be claimed that this process is really different from the generalization task, being concerned mainly with considerations of data storage. It follows, then, that the use of data reduction methods serves no useful scale-driven generalization function.

There are also other problems with approaches through data reduction. The generalized line may exhibit closing spikes that give a topologically-distorted view of line morphology. According to Thapa (1988), this problem becomes particularly serious when the process involves drastic reductions of the number of points originally used to represent the line. The problem arises because points on the line segments may collide, or nearly collide, with other points or segments. This type of pathological situation is very frequent and, more seriously, some data reduction methods will even happily produce self-crossing lines. Some typical examples are given in Muller (1990).

The Douglas data reduction algorithm is generally regarded as being the most elegant among the existing methods for line generalization (see McMaster 1983, White 1985), despite some basic and fundamental problems associated with it. It appears, therefore, that data reduction methods are probably doomed to fail as a strategy for

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[2] The characteristics of the line feature exhibited in figure 2 are completely different from those shown in figure 1. This has been demonstrated by Li and Openshaw (1990 b) through the comparison of frequency spectra. Even with a much larger tolerable distance used for figure 2 (*d*), it cannot produce a result similar to figure 1 (*d*).

line generalization and that, if further progress is to be made, then new methods are required that are free from the risk of endemic spatial conflicts. Questions might also be asked about the viability of data reduction tools that, even without scale changes, can cause irreparable damage to complex line segments.

It is clearly desirable to consider an alternative approach to the problem of generalization that is not based on a philosophy of data reduction and which also seems to be capable of handling a wider range of types of problem. Indeed, it would appear to be a matter of some urgency to seek to develop better automated methods which are based on some theory that is relevant to the generalization process and capable of producing results that are, in practice, consistent with what might be expected from manual cartographic methods.

2.3. *A new approach*

The starting point with a theory-based approach is to view the map generalization process as an integrated whole. An attempt can then be made to develop a common logical model of the process from which feature specific algorithms can be developed. The discussion later in § 3 gives a general description of some of the many different phenomena which exhibit what is termed a natural generalization process. By observing these phenomena, a natural principle has been identified (see Li and Openshaw 1990 a). Based on this self-evident natural principle, a family of new algorithms has been developed to provide a new approach to the problems associated with map generalization. It is noted that these methods are in general applicable to the generalization of other types of geographical objects.

3. **Methods based on an objective principle for map generalization**

3.1. *Theoretical background*

The objective then is to develop a theory-based procedure that is widely applicable and capable of providing a form of map generalization that is consistent with what might be expected from the application of manual methods. In developing such a method, two critical problems need to be tackled. The first is the derivation of a logical model of the generalization process that is universally applicable, and the second is the development of algorithms to operationalize the desired approach. A key design criterion is the need for a single locally-adaptive method which will perform well on all types of line data regardless of the complexity of features.

3.2. *A logical model for the generalization process*

It is fairly obvious that when an object moves away from an observer the image of the object becomes progressively smaller, so that less and less detail about the object can be seen In such a case, the image of the object is regarded as being generalized; indeed, this is the type of generalization process that can be observed in nature. This suggests that, given the limitations on the resolution of the human eye and also of graphic presentation media, there is a limit to the resolution of any map-related data that can be displayed on a given output device. As a result, there must, for any given map scale, be a minimum size of cartographic map object (viz. linear feature or polygon) beyond which virtually all detailed information is lost. This summarizes the main point of the principle which underlies what is perceived to be the natural generalization process found in nature (Li and Openshaw 1990 a). For example, with a display of fixed resolution, as the map scale changes so a large polygon becomes a small polygon. Eventually it reaches a critical size when it can be represented only as a point.

Subsequently the point itself may disappear from view. Based on this simple natural principle, new algorithms for the generalization of digital map data can be developed.

3.3. *Basic parameter: the size of smallest visible object* (*SVO*)

A critical parameter in any of the algorithms that seeks to operationalize this natural principle of objective generalization is the size of the smallest visible object (SVO). This could be a circle or a raster. For the sake of simplicity, only the circular SVO will be considered in this section. This parameter is important because it effectively controls, at the atomic level (i.e., very high resolution), the finest cartographical detail that can be seen. Of course, its absolute value has to be related in some way to map scale. At first sight, the mathematical formula which seems appropriate might be expressed as follows:

$$F_c = S_t \times D \tag{1}$$

where, S_t is the scale factor of the map to which the generalization is carried out; D is the diameter of the SVO at the map scale (in terms of map distance), within which all detailed information can be neglected; and F_c is the corresponding diameter of the SVO in terms of ground distance.

However, this equation fails to take into consideration the scale factor (S_f) of the original map (before generalization). It can be imagined that the value of F_c should also be related to S_f. In an extreme example, if $S_f = S_t$, then no generalization should be performed so that the value of F_c calculated from equation (1) should be equal to zero. Therefore, equation (1) is appropriate only for generalization from the 1 : 1 scale (no generalization) map to a 1 : S_t scale. In other words, the value of F_c in this case is the ideal value in terms of ground distance. Thus the parameter D in equation (1) can be termed the *ideal size* of the SVO at map scale S_t.

Clearly equation (1) has to be modified in some way. The following seems more appropriate and is used here:

$$F_c = S_t \times D \times (1 - S_f/S_t) \tag{2}$$

The important task now is to find a suitable value for D which is the ideal size at map scale S_t within which all detailed information can be neglected. Muller (1987) suggests that a value of 0·4 mm at map scale (i.e., in terms of map distance) is the minimum needed to ensure visual separability. This is based on the thickness of the plotting pen and the resolution of the human eye. This value might be used as the ideal size of the SVO (i.e., either circle or raster). The question as to whether such a value (0·4 mm) is the most appropriate lies outside the scope of this article and will need to be tested in future studies.

4. Three algorithms and test results

The next step is to convert the general principle of objective generalization into algorithms than can be applied to any geographical line, including complex lines similar to those in figure 1 (*a*).

4.1. *Vector mode algorithm*

It is useful to start by developing an algorithm which operates in vector mode. This algorithm is described as follows:

Step 1: Estimate the size of the circular SVO; F_c from equation (2);

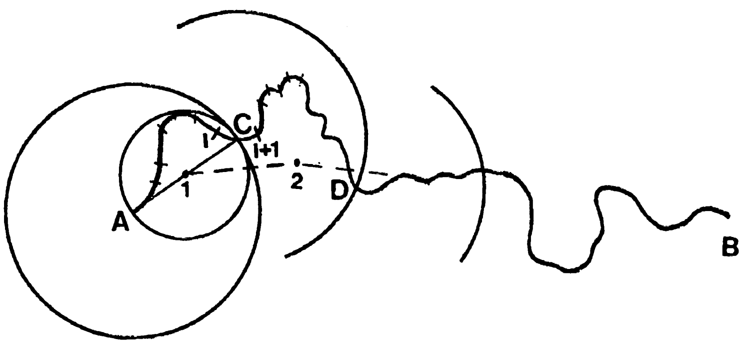
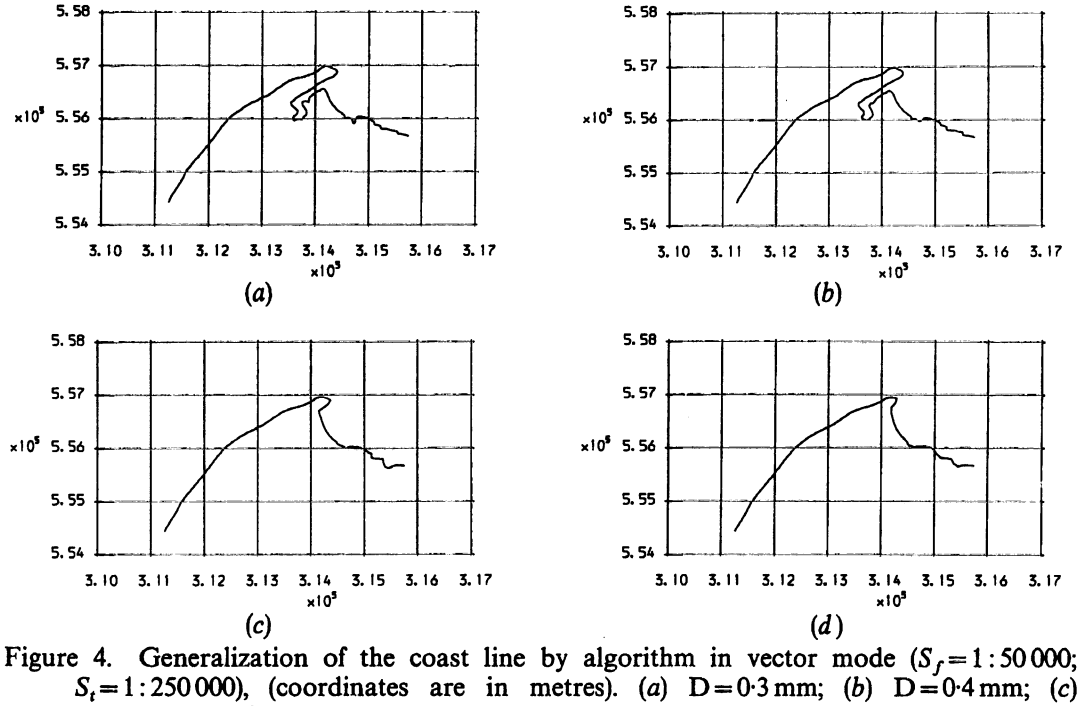


Figure 3. Line generalization in vector mode.

Step 2. Determine the location of the first circular SVO. In figure 3, A is the starting and B is the end point for the string that is to be generalized. Starting at point A, a larger circle is drawn, with radius double that of the circular SVO. The circle intersects the string at point C which is between points I and I + 1. Using line AC as the diameter, a smaller circle—the so-called circular SVO—can be then drawn, which is contained within the first larger circle. Point 1 in figure 3 is the centroid of this circular SVO.

Step 3. The area covered by the circular SVO is represented by its centroid—the mean value of the coordinates of point A and the intersection point C in figure 3. The coordinates of the intersection point C can be calculated by the following two equations:

$$\left.\begin{aligned} (X-X_A)^2+(Y-Y_A)^2 &= F_c^2 \\ \frac{Y-Y_I}{Y_{I+1}-Y_I} &= \frac{X-X_I}{X_{I+1}-X_I} \end{aligned}\right\} \tag{3}$$



(*a*) (*b*)

(*c*) (*d*)

Figure 4. Generalization of the coast line by algorithm in vector mode ($S_f = 1:50000$; $S_t = 1:250000$), (coordinates are in metres). (*a*) D = 0·3 mm; (*b*) D = 0·4 mm; (*c*) D = 0·75 mm; (*d*) D = 1·0 mm.

Step 4. Now move the circular SVO forward to another point on the line segment. The last intersecting point is always used as the new starting point to define the next new larger circle, so return to Step 2. In this way, the whole line segment can be generalized (see the dotted line in figure 3).

Figure 4 shows some of the results obtained by this algorithm for the coastline data shown in figure 1 (*a*). For the sake of clarity the scale factors in equation (2) are held constant and only the parameter D is varied. The results for four different Ds are displayed.

The results reflect the choice of this circular SVO diameter (D) and perhaps also the position of the point at which the first circular SVO is drawn. This latter problem can be overcome by overlapping successive circular SVOs by a small amount. For example, in determining the second circular SVO, a point in between points A and C along line A–C may be used instead of point C itself to locate the second circular SVO. In this case, step 4 needs to be modified. Indeed, overlapping successive circular SVOs is also a very important feature of this algorithm.

4.2. *Raster mode algorithm*

In vector mode, the generalization process involves the use of circular SVOs and the determination of the point at which the circle intersects the string to be generalized. This can be computationally expensive so an algorithm that operates in raster mode might be a useful development.

The basic idea here is to use a raster SVO instead of a circular SVO. This makes the method much simpler and faster to apply. The process is illustrated in figure 5. The algorithm is as follows:

Step 1. Set the size of raster (F_c) using equation (2).

Step 2. Determine the location of the first raster. In figure 5 points A and B are the start and end points respectively. With point A as the centre, a raster with size F_c is generated.

Step 3. The coordinates of the centre of the raster, i.e. point A in this example, is used to represent the content or area of this raster.

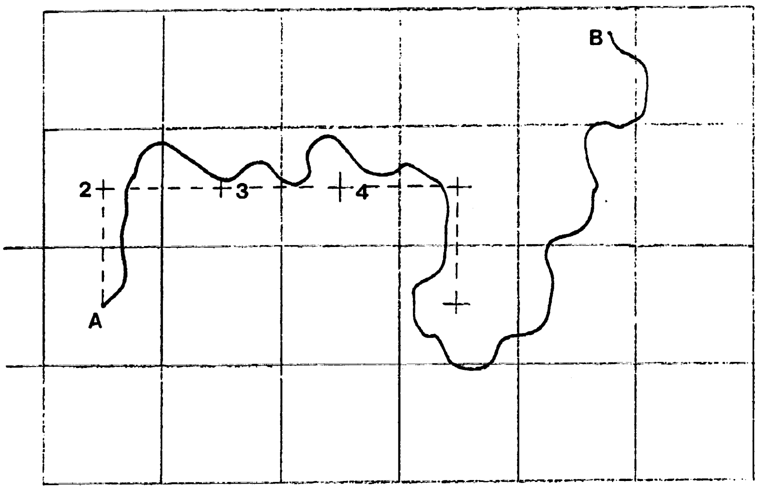
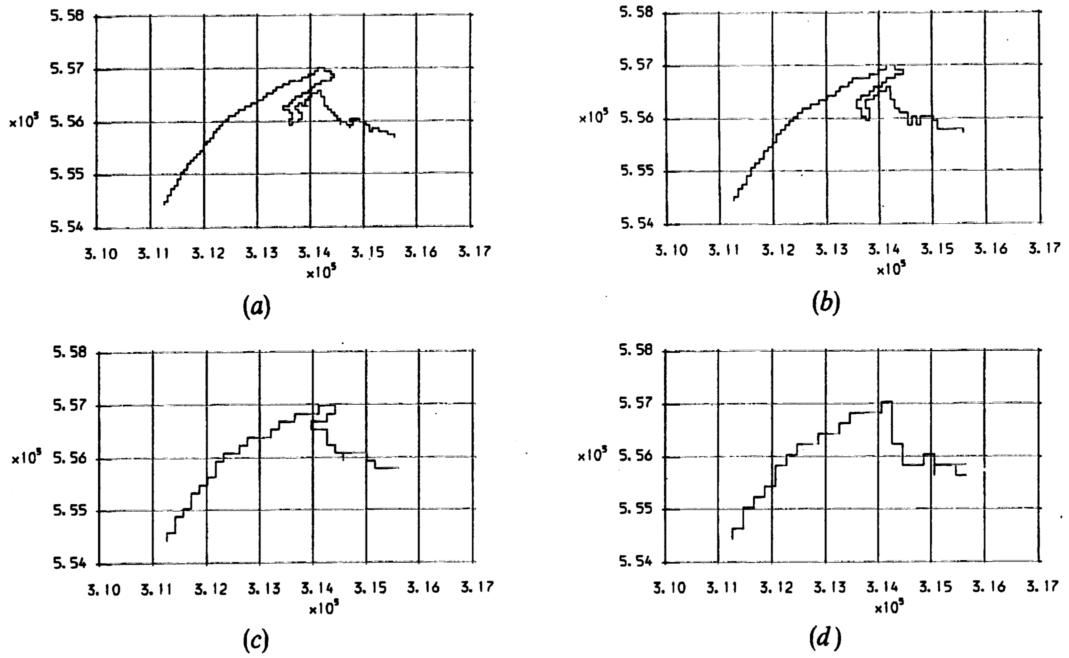


Figure 5. Line generalization in raster mode.

Step 4. Now determine where to locate the next raster. As shown in figure 5 there are four standard directions to search for the next raster location, i.e., up, down, left and right. For example, if the 'up' of the raster intersects the string to be generalized, then the second raster to be considered is the one centred at point 2.

Step 5. Repeat the process. The centre of the new raster is always used to represent the content covered by the raster. For example, the centre of the second raster, point 2 in figure 5, is used to represent the area covered by the second raster. The location of the next raster is found according to Step 4. This process is repeated so that the whole line is generalized (see the dotted line in figure 5).



(*a*) (*b*) (*c*) (*d*)

Figure 6. Generalization of the coast line by algorithm in raster mode ($S_f = 1:50000$; $S_t = 1:250000$), (coordinates are in metres). (*a*) D = 0·3 mm; (*b*) D = 0·4 mm; (*c*) D = 0·75 mm; (*d*) D = 1·0 mm.

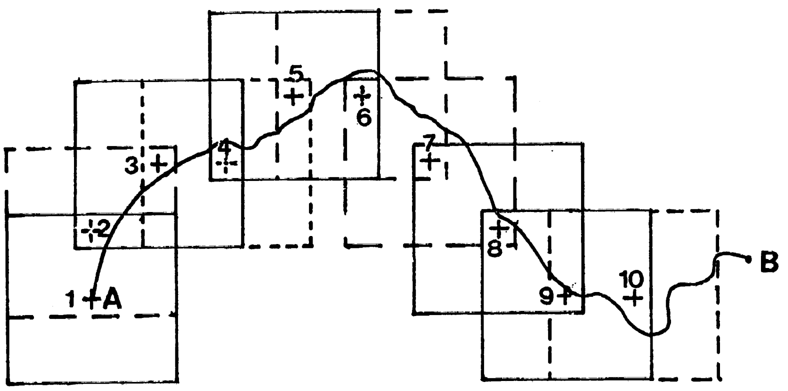
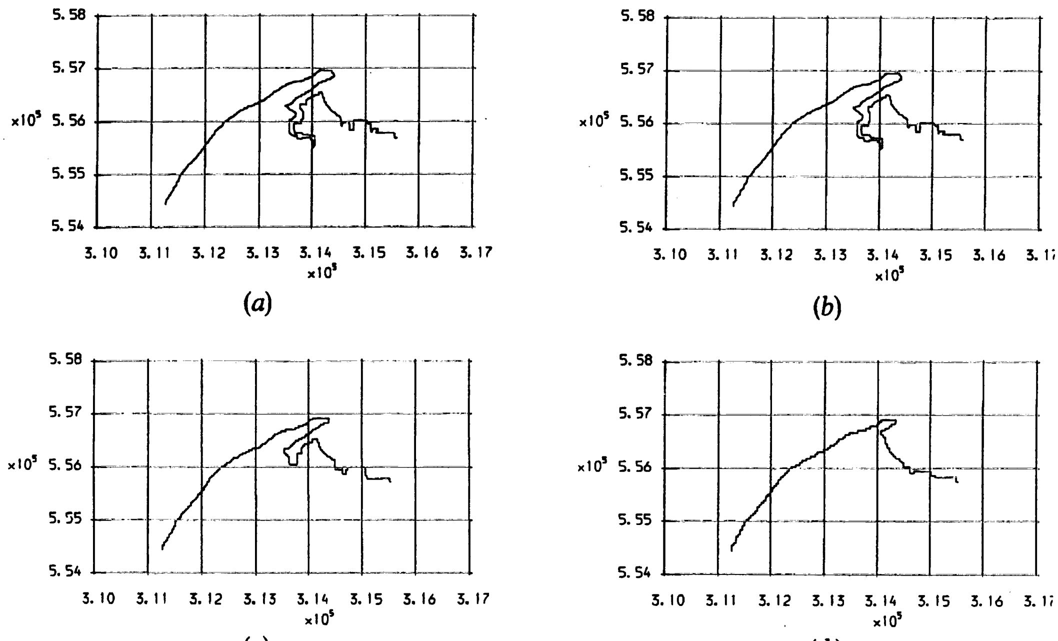


Figure 7. Overlapping between successive rasters; Points 1, 2, and 10 represents the centres of the overlapping rasters.

Figure 6 shows some of the examples generated by this algorithm from the given coastline shown in figure 1 (*a*). Once again there are four different D values. In this case, no overlap occurs between any two successive rasters[3]. However, as in the vector case, overlap between two successive SVOs can be introduced. To do this, step 4 needs to be modified so that a location between points A and 2 along line A-2 is used as the centre for the second raster; also with the size F_c. Figure 7 shows the effect of the overlapping between successive SVOs and figure 8 shows some of the examples generated by this method. The result is much more pleasing to the eye than that shown in figure 6.

4.3. *Raster-vector algorithm*

The results demonstrate that, whilst the raster mode algorithm is easier to implement and faster to run than a vector mode algorithm, the latter produces relatively smoother features. It seemed sensible, therefore, to investigate an algorithm that is based on a combination of both vector and raster approaches. In this hybrid case, the location of the recorded points is determined according to the vector algorithms but the method is then run as in raster mode. In figure 9, a point—E in this example—is the mid-point of the coordinate of points C and D and is used to represent the new point of the generalized line (i.e., the dotted line in figure 9) instead of point 2, as in the raster mode algorithm.



(*a*) (*b*)

(*c*) (*d*)

Figure 8. Generalization of the coast line by algorithm in raster mode with 80% overlap between two successive rasters ($S_f = 1:50000$; $S_t = 1:250:000$), (coordinates are in metres). (*a*) D = 0·3 mm; (*b*) D = 0·4 mm; (*c*) D = 0·75 mm; (*d*) D = 1·0 mm.

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[3] Raster, by definition, is a gridded tessellation and its grid cells will not overlap. However, overlap of grid cells as shown in figure 7 can be achieved by shifting two identical gridded tessellations by any amount less than the cell size. It is the introduction of the overlap between grid cells that makes this algorithm distinct. The question as to the optimum degree of overlap is a matter of further study but it is seemingly not too critical.

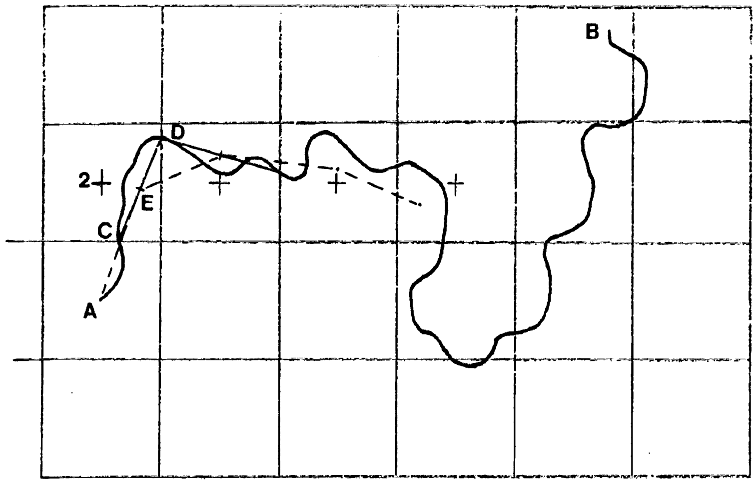


Figure 9. Line generalization in raster-vector mode.

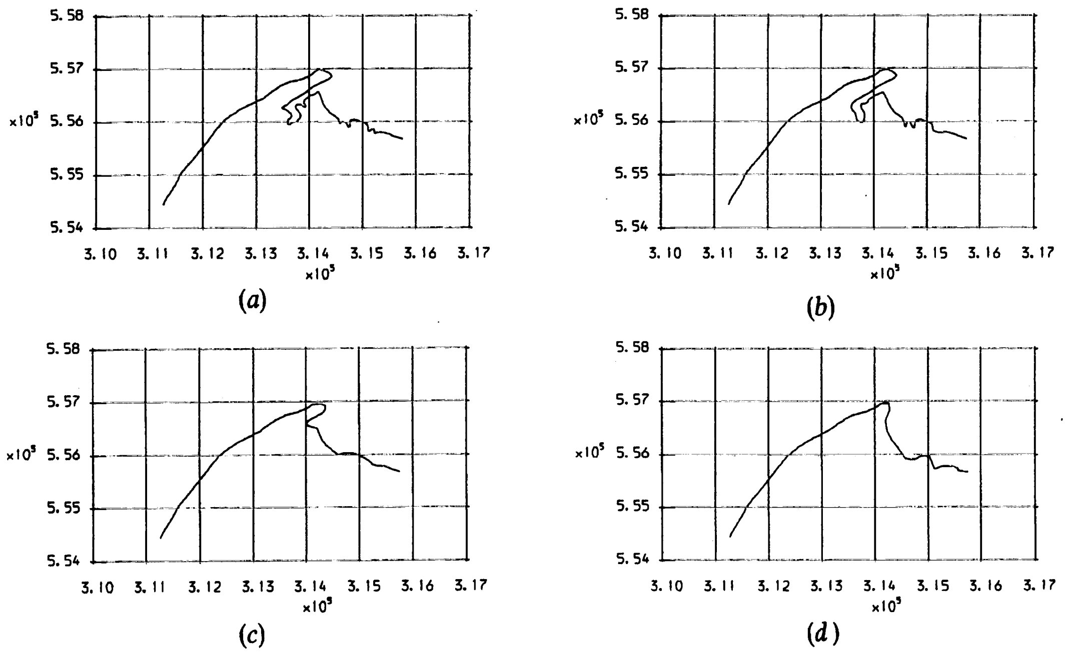


Figure 10. Generalization of the coast line by algorithm in raster-vector mode ($S_f = 1:50\,000$; $S_t = 1:250\,000$), (coordinates are in metres). (*a*) D=0·3 mm; (*b*) D=0·4 mm; (*c*) D=0·75 mm; (*d*) D=1·0 mm.

Figure 10 shows the results of applying this hybrid algorithm to the same coastline data. Again, overlap between two successive raster SVOs can be introduced in the same way as in the case of raster mode algorithm.

5. A comparison with other methods

The new methods seem to work, and the question is now how well they perform in comparison with other approaches. A comprehensive in-depth comparison is beyond the scope of this article and is reported elsewhere (Li and Openshaw 1990 b). Attention here is focused on only one example. It was clearly undesirable to use either a pathologically complex feature or a trivially simple one. A good compromise for illustrative purposes is the river segment shown in figure 11. Figure 11 (*a*) was digitized

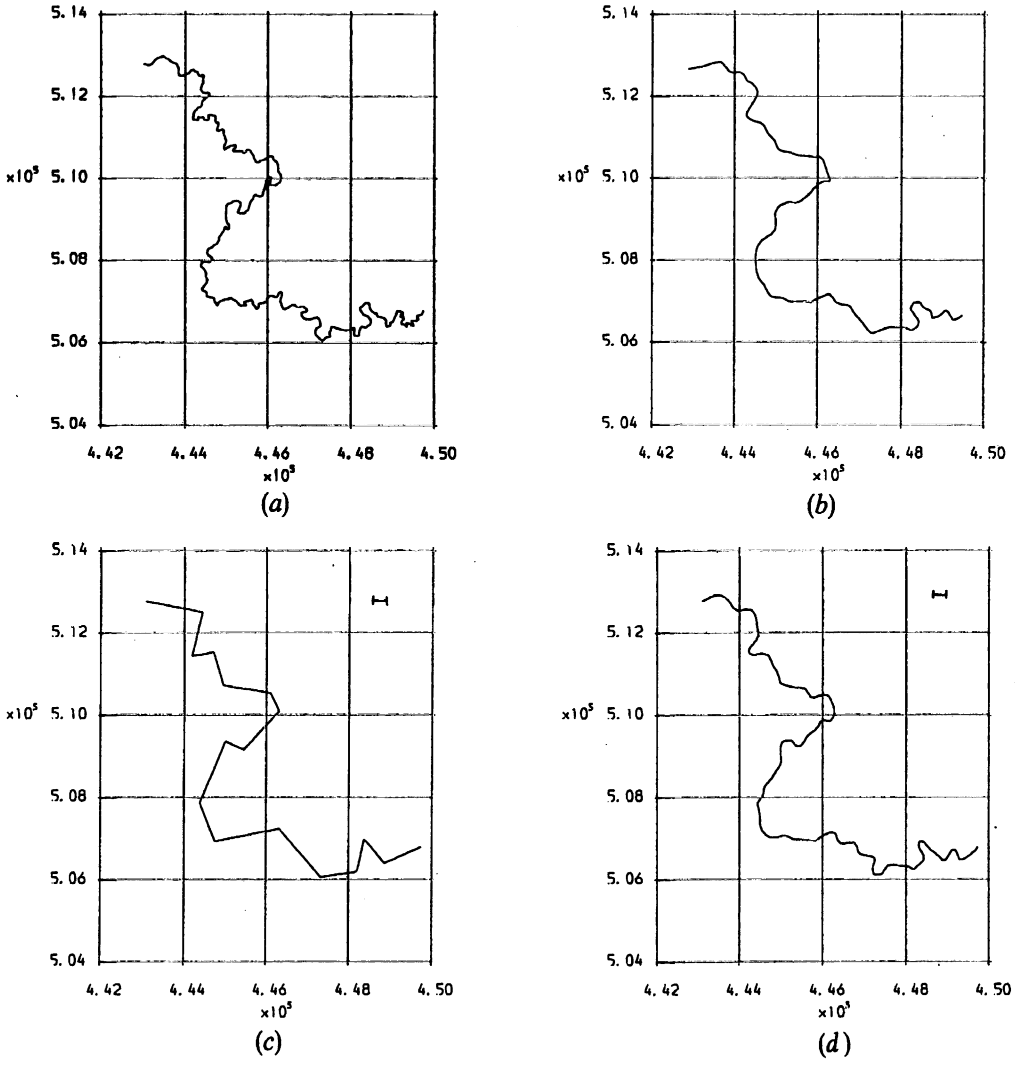
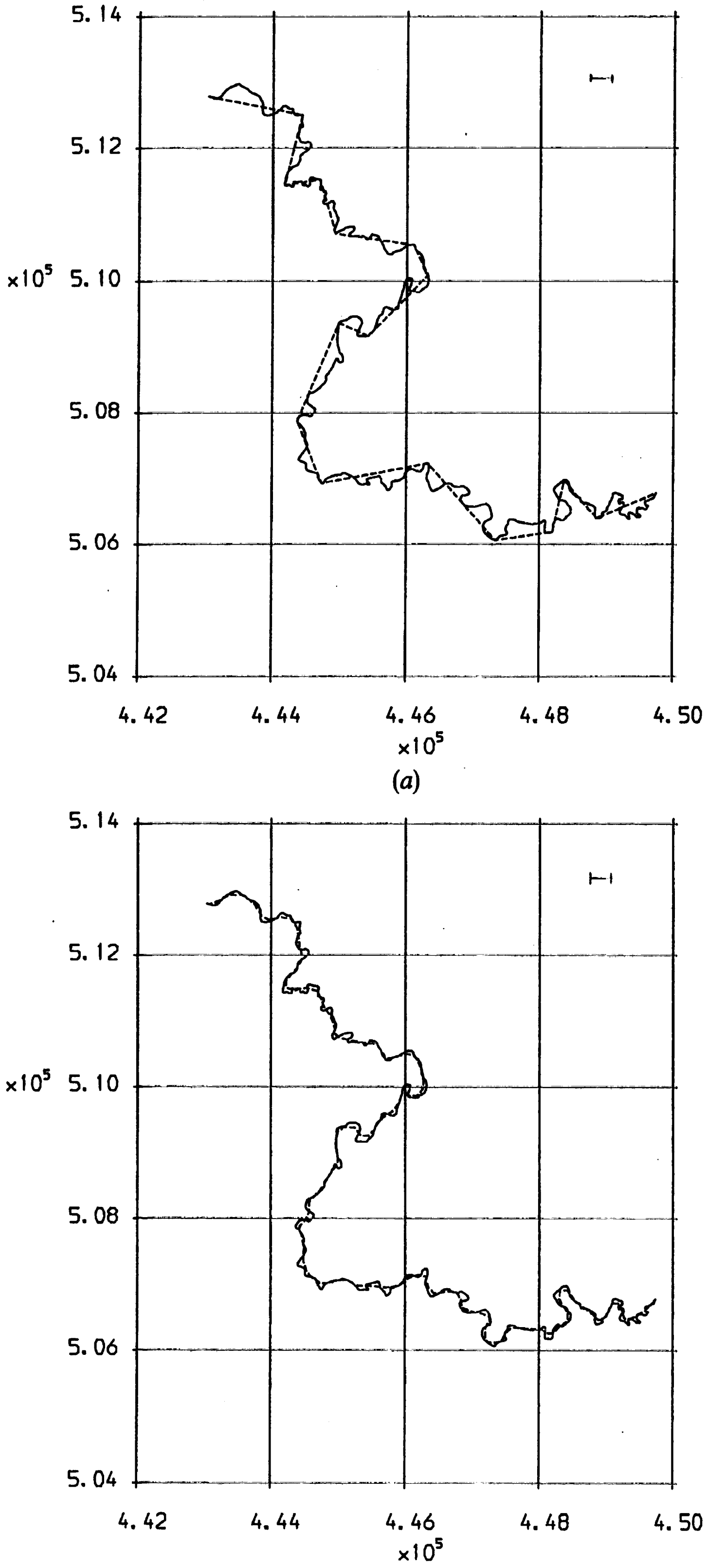


Figure 11. Generalization of a river segment by various methods. (*a*) A river segment digitized from 1:10 000 scale map; (*b*) The river digitized from 1:625 000 scale map (which is manually generalized); (*c*) The river generalized from 1:10 000 scale to 1:625 000 scale by Douglas data reduction algorithm; (*d*) The river generalized from 1:10 000 scale to 1:625 000 scale by the raster-vector algorithm.

from a 1:10 000 scale map and figure 11 (*b*) from a 1:625 000 scale map. The aim was to compare the results of the Douglas data reduction algorithm with the new raster-vector mode algorithm in generalizing the data shown in figure 11 (*a*) to a 1:625 000 scale. The results could then be compared with the manual cartographic generalization in figure 11 (*b*). A value of 0·5 mm (at map scale) was used as the size of the raster SVO for the new algorithm and the same value was used as the tolerable distance (in terms of map distance) for the Douglas data reduction algorithm. Figure 11 (*c*) shows the results produced by the Douglas data reduction algorithm and figure 11 (*d*) those by the new algorithm.

An indication of the faithfulness of the generalized results can be obtained by superimposing the computer-generated and manual results. Figure 12 (*a*) shows the results for the Douglas data reduction algorithm and its original, and figure 12 (*b*) that produced by the new algorithm. A visual inspection of figures 11 and 12 reveals that the



(a)

(b)

Figure 12. Superimposition of river segments (1 : 625 000 scale) generalized by various methods on to their original (1 : 10 000). (*a*) The river generalized by Douglas algorithm with a tolerable ground distance of 312·5 m (0·5 mm × 625 000) and its original (solid line); (*b*) The river generalized by raster-vector algorithm with $d = 0{\cdot}5$ mm and its original (solid line).

new algorithm appears to produce a much more reasonable and realistic result, in terms both of the fidelity of the generalized feature to its original and of the similarity of the generalized feature to the manual results. Various empirical measures might be helpful to quantify these impressions[4].

It is sufficient here to note that the performance of the new algorithm is quite impressive.

6. Discussion and conclusions

This article presents a set of algorithms for line generalization that operate in three different modes, i.e., vector, raster and raster-vector. Limited tests show that these algorithms can produce very reasonable results that are similar to those produced by manual methods. The authors prefer the hybrid raster-vector algorithm, which combines convenience of implementation with smoothness of results and speed of computation.

The new method is not without problems and there are undoubtedly different ways of operationalizing the natural principle of objective generalization on which it is based. In searching for positions at which the circular SVO (or raster) intersects the line being generalized, it is possible that more than one such position exists, particularly if the line segments are close together and represent a complex shape. In this case, it can be imagined that it is the last intersection point that matters and minor features which are grouped together can be ignored, because the circular (or raster) SVO itself represents the smallest unit within which no further details can be separated (and then presented) at the given scale. Such a treatment therefore, is theoretically sound. With the suggested method, for large loops connected by very thin bottle-necks, there are two

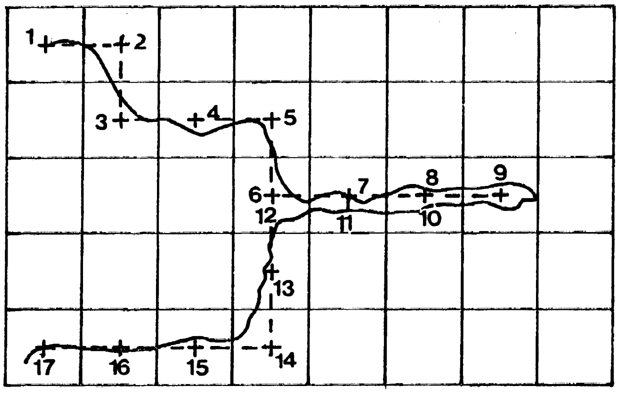


Figure 13. The selection of inadequate points may lead to line crashing. That is, the line segment consisting of points 6, 7, 8 and 9 crashed with the line segment consisting of points 9, 10, 11 and 12. In fact, this crashed line segment should be removed.

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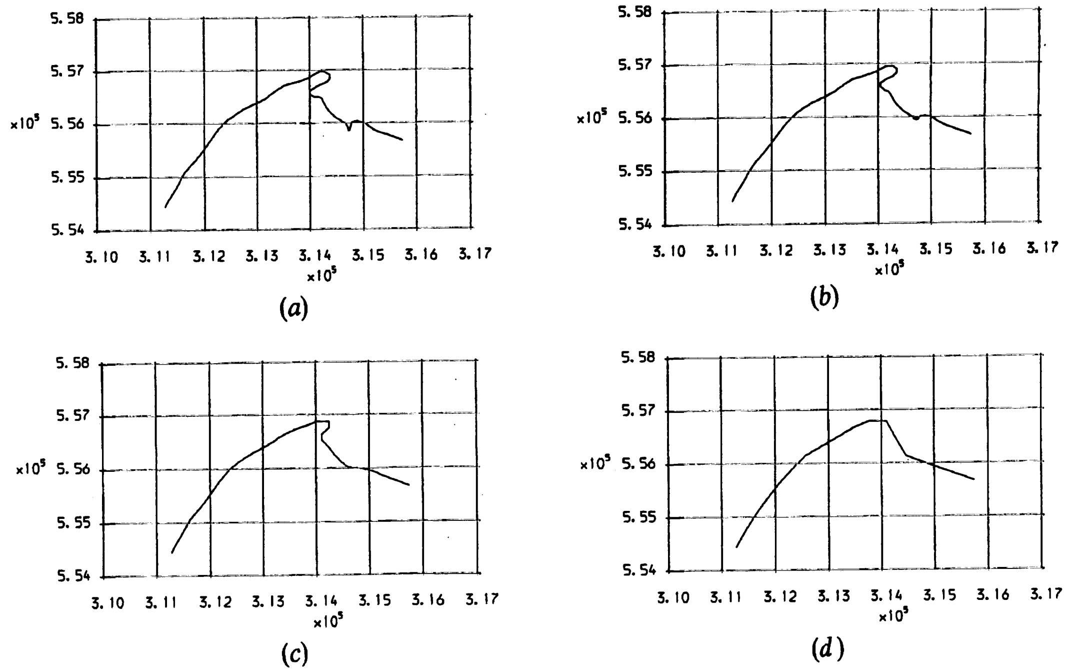
[4] In seeking to understand the effects of generalization on the characteristics of linear features, it is useful to have some numerical measures which can be used to compare manual generalization with methods of automated generalization. McMaster (1986) described thirty possible measures. However, Visvalingam and Whyatt (1990) pointed out that many of these measures are 'inappropriate, misleading and questionable'. Therefore, a discussion of the comprehensiveness of these measures and other possible measures must be undertaken before any numerical comparison can be made. This is too large a topic to be included in this article but is addressed elsewhere (Li and Openshaw 1990 b). This omission does not detract from the purpose of the present article, since the visual comparisons shown here are quite adequate to establish that the new approach is potentially very useful.

possible results generalization. If the bottle-neck is larger than a raster (or circular) SVO, nothing particular will occur; but if it is thinner than the SVO element, then the two loops will be separated. On the other hand, if the nearest point is selected, then two line segments which are very close together will be crashed together as a line (see figure 13), although self-crossing can be protected by the raster-based algorithms. This is not acceptable since, with the given size of raster SVO, the spikes in figure 13 are too thin to be separated (and then presented). On the other hand, if a post-processing procedure is followed to remove the overlapping points, i.e. points 7, 8,... and 11 (which represent the crashed lines, if any), then this could be more efficient.

Another aspect concerns the value assigned to the *D* parameter. Experience gained by the authors shows that a value of 0·5 mm or 0·6 mm might be very suitable. Figure 14 shows what happens when *D* is equal to 0·5 mm. It can be seen that these results are quite in accordance with the broad trend shown in figure 1. Further research here might be useful, and it may even be feasible to calibrate the generalization process in a more formal manner, or else make it adaptive to the nature of the line segments being generalized.

Another key factor is the degree of overlapping. If figure 6 is compared with figure 8, it can be noted that much more (but maybe too much) detail can be retained, with 80 per cent overlap between successive SVO elements. Again the question of how overlap affects the final results needs further attention, although it is argued that in both cases this amounts to little more than fine tuning.

From the results presented here, it can be concluded that these new algorithms based on a natural principle of objective generalization appear to be both general-purpose and able to produce good quality results, which may well be better than those



(*a*) (*b*)

(*c*) (*d*)

Figure 14. Generalization of the coast line from 1:50 000 scale to 1:2 000 000 by the algorithm in raster-vector mode with D = 0·5 mm but without overlap between two successive rasters. (*a*) From 1:50 000 scale (original) to 1:250 000; (*b*) From 1:250 000 scale (generalized) to 1:500 000; (*c*) From 1:500 000 scale (generalized) to 1:1 000 000; (*d*) From 1:000 000 scale (generalized) to 1:2 000 000.

achieved by other automated methods and are virtually similar to those produced by traditional cartographical means. However, further research is needed into certain algorithmic and operational aspects, together with an extension of this general method to deal with other types of geographical information that may need to be generalized. It would also be interesting to generalize a complete large digital database and investigate both the quality of the result and the computational problems this might involve. This would be instructive since, for the first time, it would be possible to view maps that are true to display scale, free of the artistic exaggerations of the traditional cartographer. All these tasks are very important. Furthermore, as the resolution of computer displays increase and costs of data storage continue to fall, so the need for automated but intelligent map generalization as a integral part of the zoom process will increase. This is an area where current GIS are gravely deficient but it is also one where future GIS will have to become very proficient if map displays are not to become increasingly polluted with vast amounts of unnecessary detail and other information inappropriate for the scale and resolution of the display.

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