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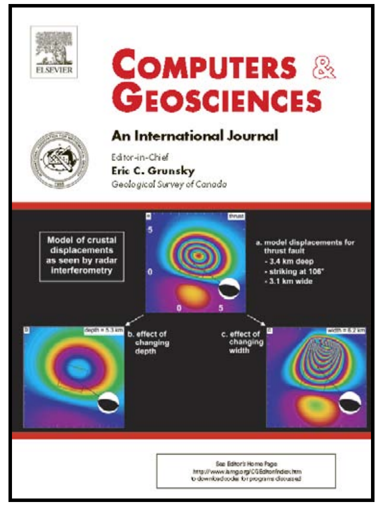

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AUTOMATIC GENERATION OF HYPSOMETRIC LAYERS FOR SMALL-SCALE MAPS

Anna M. Leonowicz*, Bernhard Jenny, Lorenz Hurni

Institute of Cartography, ETH Zurich, Wolfgang-Pauli-Str. 15, 8093 Zurich, Switzerland

*Corresponding author. Tel. +41 44 633 3018, fax +41 44 633 1153

E-mail addresses: anna.leonowicz@karto.baug.ethz.ch, jenny@karto.baug.ethz.ch, hurni@karto.baug.ethz.ch

Abstract: This paper describes a new method for hypsometric tinting for small-scale maps. The method generalises digital elevation models by removing small unnecessary details and accentuating major valleys and ridgelines. The elevation data are filtered with lower and upper quartile filters that are combined using a drainage network. The lower quartile filter is applied in valleys, delimited by the drainage network, the upper quartile filter is used elsewhere. The level of generalisation is adjusted by simplifying the drainage network with an algorithm that removes the shortest streams. The resulting hypsometric layers match the quality standards of manually generalised reference layers and are appropriate for small-scale mapping.

Keywords: DEM generalisation, hypsometric tinting, small-scale terrain mapping

1. Introduction

Hypsometric tinting is a popular method for representing relief on small-scale maps, often in combination with shaded relief. In the pre-digital era, contours were drawn manually and hypsometric tints applied to the area delimited by the contours. Delineating the hypsometric layers was a demanding and time-consuming task. Nowadays, it is easy and quick to compute discrete colour layers or continuous colour gradients from a digital elevation model, and many software applications offer this functionality (Brewer, 2005; Patterson, 1997; Schmalz and Kowanda, 2007).

Mapmakers have used hypsometric tints for over two hundred years. (Wallis and Robinson, 1987). Historically, academic cartographers pursued research in two directions: (1) the choice of hypsometric colour sequences, and (2) the generalisation of contour lines delimiting hypsometric layers. In the 19th and the first half of the 20th century, the question as to whether certain colour sequences could create a three-dimensional effect was of real interest. This interest culminated in the controversy between the Austrian school of cartography propagating colour schemes that became darker or more saturated with increasing elevation and supposedly generated a three-dimensional effect – and the Swiss style of mapping that proposed natural colour schemes with the principle “the higher the brighter” (Kretschmer, 1988, 2000). The choice of colour for hypsometric tinting is not a controversial topic of research anymore – practicing cartographers choose colour schemes according to tradition and their client’s wish.

However, the generalisation of digital elevation models for hypsometric tinting merits attention. Especially for small-scale mapping, an appropriate generalisation that accentuates important landforms and omits distracting details, is a challenging task. The guidelines for traditional terrain generalisation were formulated by Horn (1945), Pannekoek (1962), and Imhof (1982). The goal of the method in the pages that follow is to apply these guidelines to hypsometric layers derived from digital elevation models.

Two different methods presently exist for the digital generalisation of hypsometric layers: (1) the generalisation of the elevation model prior to the computation of hypsometric layers, and (2) the generalisation of the vector hypsometric layers derived from an elevation model. For the present study, we deliberately concentrate on the generalisation of elevation models, a procedure, which we deem potentially simpler to perform and yields more promising results. Various methods have been proposed in the literature. The simplest procedure downsamples the DEM by increasing the raster cell size using the nearest neighbour or other interpolation techniques. This approach is widely available in GIS and image processing software. More sophisticated methods were revised by Gesch (1999), McMaster and Monmonier (1989) and Weibel (1992). According to Weibel (1992) there exist three approaches: global filtering, selective filtering, and heuristic morphology-based methods. Global filtering methods were developed in the field of digital image processing. They compute a statistic measure for each output raster cell, such as the mean, median, minimum, or maximum value of neighbouring data values. Selective filtering removes insignificant elevation points, *i.e.* points that are below a predefined significance level. Heuristic morphology-based methods take important topographic features into account, for example ridge and valley lines, as well as peaks and pits, which are generalised and preserved in the output elevation model. Morphology-based methods tend to follow principles of cartographic generalisation and are the preferred solution for maps greatly reduced in scale (Weibel, 1992).

This study presents a new morphology-based DEM generalisation method that is applicable for the computation of discrete hypsometric layers at small scales. The DEM generalisation method presented here focuses on a specific cartographic need—it is not intended as a general-purpose solution for the generalisation of digital elevation models. Nevertheless, the generalisation concepts are potentially applicable to deriving other types of geo-visualisations.

2. Cartographic generalisation of hypsometric layers

The principles for relief generalisation were developed in pre-digital cartography. They were accepted and commonly used, because they were based on experience and logic, and proved effective in practice. The presented automatic method was developed according to these traditional guidelines. A critical examination of the principles was not the intension of this research.

In pre-digital cartography, the principles for the generalisation of contour lines were applied to the generalisation of hypsometric layers. The most important guidelines are according to Horn (1945):

- Main landforms should be accentuated, while secondary features should be eliminated.
- As far as possible, contour lines should retain their original position and form. Contour lines should only be displaced for improving map readability. Fig. 1 compares examples of poor and adequate generalisation. The poor generalisation excessively rounds relief forms, while the adequate generalisation faithfully retains the characteristic shapes of the terrain.
- Each landform should be treated as a whole. For example, a valley should be either retained or completely removed, but not shortened.
- Positive forms (*i.e.* mountain ridges) have priority over negatives forms (*i.e.* valleys); all positive forms should be retained; the smaller ones can be aggregated if they belong to the same bigger form (Fig. 2).
- Small negative forms (*i.e.* side valleys) should be removed (Fig. 3).
- Main valleys (negative forms) can often only be depicted if they are broadened at the expense of neighbouring smaller forms.

When hypsometric layers are manually produced according to these guidelines, the results depend to a large extent on the professional experience and on subjective decisions of the cartographer. Hence, the guidelines are recommendations that leave space for interpretation.

3. Test area and data

The Carpathian Mountains were selected as a test map for the described generalisation method, because they include a variety of relief forms, *i.e.* high and low mountain ranges, as well as flat areas with deep river valleys. The test map scale is 1:15 000 000, which is commonly used for overview maps of the European continent in geographical atlases. The Global 30 Arc Second Elevation Data Set (GTOPO30) was chosen as the source data. This freely available elevation model was compiled in the 1990s by the U.S. Geological Survey[1] and provides regularly spaced elevation data at a resolution of 30 arc seconds (approximately 1 kilometre along the equator). We consider the medium resolution and the geometric accuracy of this data set to be sufficient for hypsometric tinting at a scale of 1:15 000 000.

A set of hypsometric layers, designed according to the generalisation guidelines described in the previous section, provided a reference to evaluate the results. They were manually compiled by Ernst Spiess[2] from ungeneralised contour lines derived from GTOPO30 (Spiess, Personal Communication, 2008). These hypsometric layers were designed for an overview map of Europe at a scale of 1:15 000 000 for the future editions of the Swiss World Atlas (Spiess, 2008) and for its forthcoming interactive version[3]. Spiess' high-quality hypsometric layers (Fig. 4 left) allowed for a critical evaluation of the outcome of the automatic procedure presented in this paper, as they are at the same scale and have been derived from the same elevation model. To assess the presented method, the automatically and manually generalised hypsometric layers were only compared visually. This is to acknowledge the subjective nature of manual generalisation. A quantitative comparison would be unjustifiable.

[1] http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html

[2] Ernst Spiess is an experienced cartographer, Professor Emeritus of the Institute of Cartography of ETH Zurich, long-time editor in chief of the Swiss World Atlas, and author of various publications on cartographic generalisation and design.

[3] http://www.swissworldatlas.ch/

The hypsometric layers follow a geometric progression with steps at 0, 100, 200, 500, 1000 and 2000 meters above see level, as recommended by Imhof (1982). Geometric progressions are common in small-scale hypsometric mapping, as low relief areas can be well differentiated, and the large vertical intervals for higher elevations appropriately indicate the small patches of high mountain areas.

Fig. 4 (right) shows hypsometric layers derived from GTOPO30 elevation data without any generalisation. A comparison with the manual reference layers (Fig. 4 left) illustrates the excessive amount of topographic detail found in raw GTOPO30 data and the need for generalising the hypsometric layers for a clear portrayal of major landforms.

4. DEM generalisation for small-scale hypsometric tinting

Surprisingly few studies exist about DEM generalisation for producing cartographic relief representations at small-scales. Patterson (2001a, b) developed a technique for low-resolution elevation models called ‘resolution bumping’ and used it to visualise GTOPO30 data. The technique merges downsampled elevation data with high-resolution data to improve the legibility of mountainous areas. Other attempts for small-scale mapping were carried out by Böhm (1997) who used filtering techniques for various types of relief representations, and Prechtel (2000) who produced small-scale relief shading using a customized resampling method.

Advanced methods, such as those described above, are indeed necessary to successfully generalise digital elevation models according to cartographic principles. Simple raster-based low-pass filters, Gauss filters or non-linear median filters do not provide satisfying results, as can be seen in Fig. 5, which shows the hypsometric layers derived from GTOPO30 when a median filter with a size of

5×5 cells is applied 10 times. A visual comparison with the manual reference layers (Fig. 4 left) reveals that simple filtering leads to hypsometric layers that are not consistent with the principles of cartographic generalisation outlined in the previous section. Small mountain peaks tend to disappear, instead of being retained and aggregated (Fig. 5, box A); valleys, which should be either completely removed or retained as a whole, are shortened or split into small depression areas (Fig. 5, box B); and important mountain passes tend to disappear (Fig. 5, box C).

4.1. Outline of the method

Upper and lower quartile filters can solve the problems described above, as they tend to preserve the original elevation of ridgelines and valleys. The upper quartile filter assigns to each raster cell the 75 percentile of its neighbouring values, *i.e.* the n neighbouring cells are ordered by increasing elevation and the elevation at position $\frac{3}{4} \times n$ is assigned to the cell. The upper quartile filter preserves elevated areas and is therefore appropriate for filtering ridge areas (Fig. 6 left, box A). It also aggregates isolated small hills and mountain peaks, which is consistent with the guidelines for manual generalisation. The lower quartile filter assigns the 25 percentile of the neighbouring values to each raster cell. It broadens valley bottoms and better preserves them from being dissected in unconnected depressions (Fig. 6 right, box B). The lower quartile filter also retains mountain passes (Fig. 6 right, box C).

Our method combines the upper and the lower quartile filter. The general principles are to (1) filter the elevation model with an upper quartile filter to produce a first model that is appropriate for ridge areas; (2) apply a lower quartile filter to produce a second model that is appropriate for valley bottoms; and (3) combine the two models according to local morphology. The diagram in Fig. 7 shows the successive steps of the procedure. The central column in Fig. 7 outlines the generation of a grid containing weights for combining the two models. The weighting grid is generated as follows:

1. In a pre-processing step, depression artefacts are removed from the elevation model.
2. A raster drainage network is extracted from the elevation model by computing the hydrological accumulation flow using the D8 algorithm, and applying a threshold to the accumulation flow.
3. The drainage network is simplified according to the desired level of generalisation with a custom algorithm.
4. A series of thin buffers are applied to the generalised drainage network to enlarge valleys.
5. The buffered drainage network is used as weight to combine the two grids filtered with upper and lower quartile filters.

In the last step, the combination of the two elevation models filtered with upper and lower quartile filters is converted to hypsometric layers, either in raster mode by mapping the elevation values to colour codes, or by a conversion to polygons with a contouring algorithm.

The whole procedure is automatic and the resulting hypsometric layers do not require any manual corrections. Yet, the proposed method is not automatically suitable for any scale transition, but it has to be adjusted for the specific purpose and data characteristics. The approach relies on the expert knowledge of a cartographer, who visually inspects the preliminary results and interactively adjusts a limited number of input parameters until the resulting hypsometric representation is adequately generalised. The values of these parameters depend on the desired level of generalisation and the spatial resolution of the elevation model. The user needs to define the following parameters:

- The size of the upper and lower quartile filters and the number of filter passes: larger filter sizes and higher numbers of filter passes result in a stronger generalisation.

- The threshold for converting the accumulation flow to a drainage network: this threshold mainly depends on the model resolution; if the threshold is too high, valleys are undesirably shortened.
- The minimum stream length used by the custom algorithm for generalising the drainage network: a higher threshold removes more drainage segments and increases the level of generalisation.
- The number of buffers applied to the drainage network to enlarge valleys: an increased number of buffers leads to broadened valleys at the expense of neighbouring forms.

All processing steps can be carried out with commonly available GIS software. The only exception is the custom algorithm for generalising the drainage network, which was implemented in a dedicated application using the Java programming language. From a mapmaker's perspective, all processing steps should be integrated in one software application, because this would not require the user to switch between various applications and file formats.

The reminder of this section will provide more details on the various generalisation steps represented in the central column of Fig. 7, leading to a grid containing weights for the combination of the upper and the lower quartile filters. The values of the generalisation parameters given below were defined by inspecting the resulting hypsometric layers for a target scale of 1:15 000 000 and a grid cell size of 30 arc seconds. Hence, the parameter values mentioned in the following sections are only a guideline for a specific type of input data and mapping scale. They must be adjusted for other scales and model resolutions.

4.2. Detecting valleys and ridges

Numerous studies, especially in the field of hydrology and geomorphology, have been conducted to automatically detect valleys and ridges from digital elevation models. Thorough reviews are given by Douglas (1986), Tribe (1992) and Bertolo (2000). Tribe (1992) identifies three groups of approaches: (1) those based on local terrain morphology; (2) those based on drainage direction; and (3) combinations of 1 and 2. The first group, based on local terrain morphology, identifies valleys by comparing heights of neighbouring cells. The curvature coefficient is commonly used for this. Cells with a concave curvature greater than a given threshold are classified as valleys, and cells with extreme convex curvature are classified as ridges. A set of tools identifying various morphometric features from DEM were developed by Wood (1996) and implemented in LandSerf[4], a free GIS for visualisation and terrain analysis. The second group of methods based on drainage direction, extract a continuous network of valley and ridge lines. The drainage network is identified by hydrological methods, *i.e.* the accumulation flow. Ridges can be defined by this procedure as areas of no drainage (where the accumulation flow is null), as the watershed boundaries of drainage segments, or by extracting ridge lines by applying the accumulation flow algorithm on a vertically mirrored elevation model. The third group of approaches, a combination of the previous two, first discovers so called 'start' cells, *e.g.* local minima and maxima. Starting at these cells, valley and ridge lines are tracked along the slope line. Still another possibility for identifying terrain structure lines is by using edge enhancement filters (*e.g.* high-pass filter) (Weibel, 1992).

Each of the approaches described above has been used for generalising digital elevation models. For example, Böhm (2000) developed a method for detecting skeleton lines from sudden changes of aspect; Fan *et al.* (2007) generalise a DEM using profile curvature. Methods based on drainage extraction are commonly used (*e.g.* Gesch, 1999; Jordan, 2007; Li and Ai, 2007; Weibel, 1992). Yoeli (1984, 1990) developed a two-step algorithm combining morphological and hydrological

[4] http://www.landserf.org/

approaches. The edge detection technique was applied by Böhm (2000), Weibel (1992) and Zakšek and Podobnikar (2005).

The hydrological method was used to extract skeleton lines in our application. The main advantages of this solution are the continuity of the resulting valley network, and the possibility to eliminate shorter streams from the network in a subsequent step. This subsequent network generalisation is crucial for hypsometric layers at small-scales. The proposed method uses the D8 (deterministic eight-node) algorithm by O'Callaghan and Mark (1984), because it is available in various software packages and computationally efficient. The algorithm computes a drainage network by simulating the flow of water on the DEM. First a flow direction is defined for each cell, which is the direction of the steepest path flowing into one of the eight nearest neighbours. The value of accumulation flow is then calculated for each cell as the number of cells draining into this cell (Wilson and Gallant, 2000).

After computing the accumulation flow with the D8 algorithm, cells with a value exceeding a given threshold can be qualified to be part of the drainage network. The higher the chosen threshold, the lower the density of the resulting network will be. For GTOPO30 data at a scale of 1:15 000 000, we assigned cells with more than 50 contributing cells to the network.

4.3. Buffering the drainage network

Applying a threshold to the accumulation flow results in a drainage network that is very narrow, usually only one pixel in width. When using the network for combining upper and lower quartile filters, valley bottoms in the resulting hypsometric layers would be very thin. To remedy this, the grid with the drainage network is first converted to a binary grid, *i.e.* cells that are part of the network are set to 1, while all other cells are 0; and buffers are then built around the cells of the drainage network to broaden the valley bottoms. When a series of narrow buffers with gradually decreasing value is applied, a smooth transition can be generated for areas where the lower and the upper quartile filter meet. Hence, the resulting drainage network is widened and creates a gradient transition between valley bottoms and the surrounding areas. For GTOPO30 data at a scale of 1:15 000 000, the drainage network was buffered 5 times with a buffer width of 1 cell. Fig. 8 shows a buffered drainage network as thick dark lines. The lower quartile filter is used in dark areas and the upper quartile filter is applied elsewhere. The drainage network in this figure is already generalised with the method described in the following section.

The resulting hypsometric layers are shown in Fig. 9. When comparing this with the median filter of figure 5, the following advantages can be identified: (1) small hills and mountain peaks do not disappear, but tend to be aggregated (box A); (2) valleys are not shortened or split into parts (box B); and (3) mountain passes are retained (box C). However, the hypsometric layers are still too detailed. To further generalise the elevation model (and hence the resulting hypsometric tint layers), the shortest streams must be removed from the drainage system. Increasing the threshold when converting the accumulation flow into the drainage network is not an option, because this would not only remove the shortest lines, but would also truncate longer streams.

4.4 Generalising the drainage network

To further simplify the drainage network the process of manual river generalisation should be imitated: lines that are shorter than a predefined threshold should be removed as a whole, while longer lines should be retained in their entirety. A common technique to simplify drainage networks uses stream ordering of drainage segments. Stream ordering reflects the topological order in the river network, beginning at the sources and ending at outlets. Streams with a low order are removed from the network. The Horton ordering was found to be the most adequate for the cartographic generalisation of river networks (Rusak Mazur and Castner, 1990) and it was utilised in different generalisation studies. Thompson and Brooks (2007) used Horton ordering in combination with the 'stroke' extraction method (*i.e.* extracting straight elements from a geographical network based on principles of visual grouping) to find the longest and straightest streams in a river network. Ai *et al.* (2006) developed a river generalisation method that considers stream orders and watershed areas. Horton ordering was also utilized for DEM generalisation (Weibel, 1992, Li and Ai, 2007).

For our generalisation method, a customized raster-based algorithm was developed that only takes the cartographically relevant length of streams into account, but not the hydrological ordering. The algorithm has the advantage compared to Horton's stream ordering in that long streams with a low Horton order (*i.e.* stream segments starting close to sources) are retained. The algorithm takes a raster grid with the accumulation flow as input, which has its values limited to the aforementioned threshold of 50 contributing cells. Starting at each raster cell, the algorithm creates an upstream path by following cells that have smaller accumulation values than the current cell. The algorithm follows the path with the smallest absolute difference to identify the longest stream passing through the current cell. If the path is longer then a predefined threshold *t*, it is stored in the output raster. The value of the threshold *t* adjusts the level of generalisation, as all paths shorter then the threshold are removed from the drainage network. Examples of different levels of drainage generalisation are shown on Fig. 10. A threshold *t* of 80 cells was chosen for GTOPO30 elevation data at the scale of 1:15 000 000.

When the simplified drainage network is used as weight to combine the two grids (one filtered with the lower and one filtered with the upper quartile filter), hypsometric layers are much more generalised than with the original network (compare Fig. 9 and Fig. 11) and are closer to the desired level of detail (compare with Fig. 4 left). Small valleys are removed, while important valleys are preserved (*e.g.* two boxes labelled A in Fig. 11). Hills and mountain peaks are aggregated and the highest elevations have a compact form.

4.5. Removing depressions artefacts

Although hypsometric layers resulting from the procedure outlined so far closely match manually drawn layers, there are still several shortcomings that need to be improved. The most noticeable problem are discontinuous valleys, *i.e.* upper parts of valleys appearing as unconnected depressions (Fig. 11, three boxes labelled B). These depressions originate from artefacts in the GTOPO30 elevation data and are also present in hypsometric layers derived from the ungeneralised elevation model (Fig. 4 right). They are caused by pits *i.e.* cells that are surrounded by neighbours having higher elevation values. Problematic pits are not peculiar to GTOPO30, but are frequent artefacts of gridding processes, especially in narrow valleys, where the cell size is greater then the width of the valley bottom (Burrough and McDonnell, 2000). Such pits need to be removed from digital elevation data before the hypsometric layers are derived. Depressions can be identified automatically and are mostly small and spurious. For large depressions, a human operator has to decide whether they are natural or a model artefact (Lehner *et al*., 2006).

Spurious pits can be removed from elevation data by a filling algorithm that increases the elevation of depressions to the level of their surroundings. Pit filling is a common GIS technique, but is not a good option for generating hypsometric layers, as it unnaturally shortens affected valleys. Kenny *et al.* (2008) compare different sink-processing methods in raster elevation models, which were developed in the field of hydrology. A common solution makes modifications to the elevation values so that the flow routes replicate the known hydrology network. An alternative method was proposed by Soille *et al.* (2003). The method creates a path from the pit to the nearest point with a lower elevation. Pits are removed by ‘carving’ *i.e.* lowering elevations along this path. Details of this carving algorithm can be found in Soille (2004a). Another solution is a combination of carving and pit filling. This hybrid method first fills pits to a certain level, and then carves along a path connecting the depression (Soille, 2004b). Because the hybrid method, compared to filling and carving, causes the smallest changes in elevation, it was chosen to pre-process GTOPO30 elevation data. Pits were removed before the model was filtered and the drainage network extracted. Pits could be easily identified, since no big natural depressions exist in the study area. The merits of the pit removal technique are evident: all depressions are joined with the lower parts of the valleys (compare the areas of boxes labelled B in Fig. 11 with the same areas in Fig. 12).

5. Evaluation of results

To evaluate the proposed method, generalised hypsometric layers of five test areas were created, covering a wide range of landforms and elevation ranges from different parts of Europe (Fig. 13): high-alpine mountain relief (A – Caucasus), lower mountains (B – Carpathians), a moderately hilly plateau (C – Massif Central), low relief with big river valleys (D – East European Plain) and a coastal plain (E – Courland). GTOPO30 was used for example B, and the SRTM (Shuttle Radar Topography Mission) elevation model for all other examples. SRTM covers almost 80% of the earth's surface and provides elevation data at a resolution of 3 arc seconds (approximately 90 meters at the equator). For computational efficiency, we used SRTM30[5], a simplified version at 30 arc seconds. Fig. 14 compares the ungeneralised hypsometric layers (left column), the manual reference data (central column), and the results of the presented generalisation method (right column). The legends on the right indicate the elevation range for each example.

A visual comparison of the hypsometric layers of Fig.14 shows that in each test area our generalisation method removes many unnecessary details present in the raw elevation data. It was

[5] http://www2.jpl.nasa.gov/srtm/

possible to achieve the level of details appropriate for the test map scale of 1:15 000 000. The main advantage of the proposed method is that hypsometric layers follow the guidelines of cartographic relief generalisation: mountain ridges are aggregated and most of them are not removed during filtering; small valleys are removed while the bigger ones are retained (but not shortened).

However, when comparing digitally generalised layers with the manual reference data set some differences can be noticed:

1. A few extremely narrow valleys are split in parts, for example the Danube valley in the SW corner of the test area in Fig. 14B. The carving algorithm did not identify it as a continuous river, because both ends of the Danube valley touch the border of the test area and are therefore treated as outlets.
2. Large valleys are locally too narrow and therefore not as visually salient as required by their hydrological importance.
3. In some areas, very small mountain peaks disappear, because the upper quartile filter removes extremely small areas (*e.g.* the highest peaks of the Caucasus and Eastern Carpathians). In low relief areas, the digital layers of small hills are more detailed (*e.g.* Fig. 14D,E).

Further research could solve some of these problems. For the time being, these rare defects can be remedied manually. The necessary manual corrections can be done relatively quickly when working on the hypsometric layers, after derivation from the elevation model.

Two limitations must be noted. First, artefacts may occur in totally flat large plains, because the accumulation flow, which is used to generalise the elevation model, is not defined in these areas. Second, coastlines at sea level are generally not appropriately generalised, as the filtering and the often missing depth values in digital elevation models lead to inaccurate contours. Further research is needed to extend the method to bathymetrical layers of water bodies, which have not been considered in our research. Also, the method should be tested with different map scales, including greater scale reduction, and elevation models of different resolution.

6. Conclusions

Global digital elevation models are widely available nowadays, but visualisations directly derived from such data often do not take into account the guidelines of traditional cartography. This is not due to shortcomings of the digital data, but to the lack of methods for the proper cartographic generalisation of terrain models, particularly for small-scale mapping.

The generalisation method introduced in this paper automatically simplifies digital elevation data for the subsequent derivation of hypsometric layers at small scales. By contrast to filtering methods of standard GIS software, the presented method follows the main principles of cartographic terrain generalisation. The method preserves the elevation of the main ridges and valleys, and resulting hypsometric layers are adequate for small-scale mapping. The procedure consists of a series of basic raster operations that can be performed using standard GIS software (apart from the custom algorithm for generalising the drainage network).

In general, cartography is lacking advanced generalisation methods for terrain representation at small scales. In the future, automatic methods following principles of pre-digital manual cartography will certainly increase the quality of contemporary mapping.

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Fig. 1. Poor (left) and faithful (right) contour generalisation (Horn, 1945).

Fig. 2. Medium (left) and strong (right) aggregation of small mountain peaks (Horn, 1945).

Fig. 3. Medium (left) and strong (right) generalisation of valleys (Horn, 1945).

Fig. 4. Hypsometric layers (target scale 1:15 000 000, here enlarged by 200%). Left: manually generalised. Right: generated from GTOPO30 data.

Fig. 5. Median filter (filter size: 5×5 cells, applied 10 times).

Fig. 6. Upper and lower quartile filter (filter size: 5×5 cells, applied 3 times).

Fig. 7. Processing steps leading to generalised hypsometric layers.

Fig. 8. Buffered drainage network: dark areas indicate valley bottoms where lower quartile filter is applied.

Fig. 9. Lower and upper quartile filters combined: hypsometric layers are too detailed.

Fig. 10. Drainage network generalisation (*t* is a length threshold).

Fig. 11. Lower and upper quartile filters combined with simplified drainage network.

Fig. 12. Hypsometric layers after pit removal.

Fig.13. Locations of test areas covering different elevation ranges and landforms.

Fig.14. Hypsometric layers of landforms with different elevation ranges (elevations in meters above sea level)

Figure 1

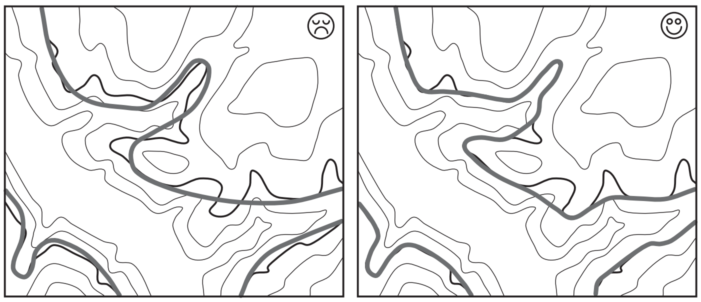


Figure 2

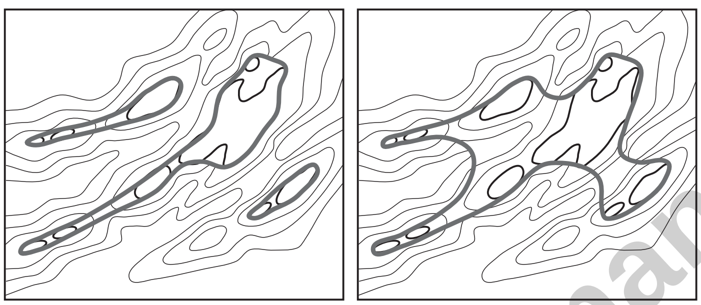


Figure 3

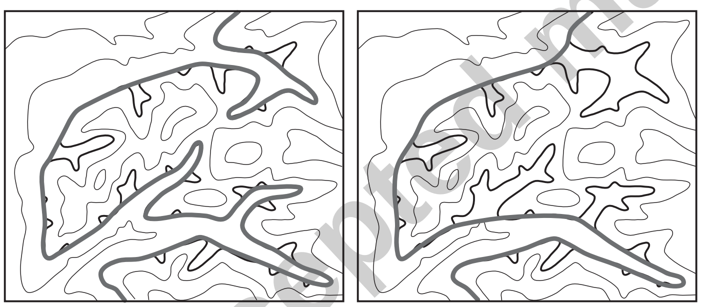


Figure 4

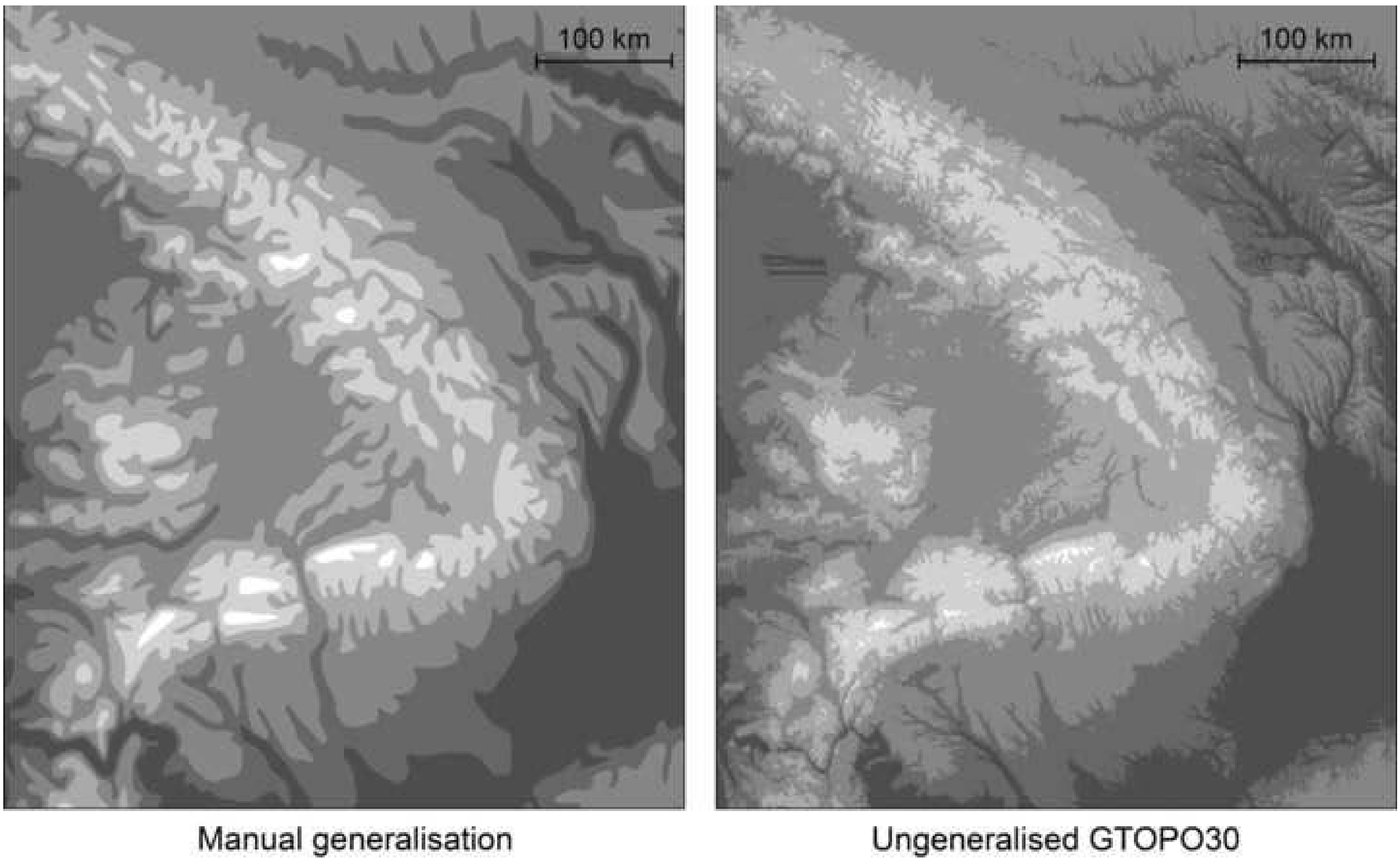

100 km
Manual generalisation
100 km
Ungeneralised GTOPO30

Figure 5

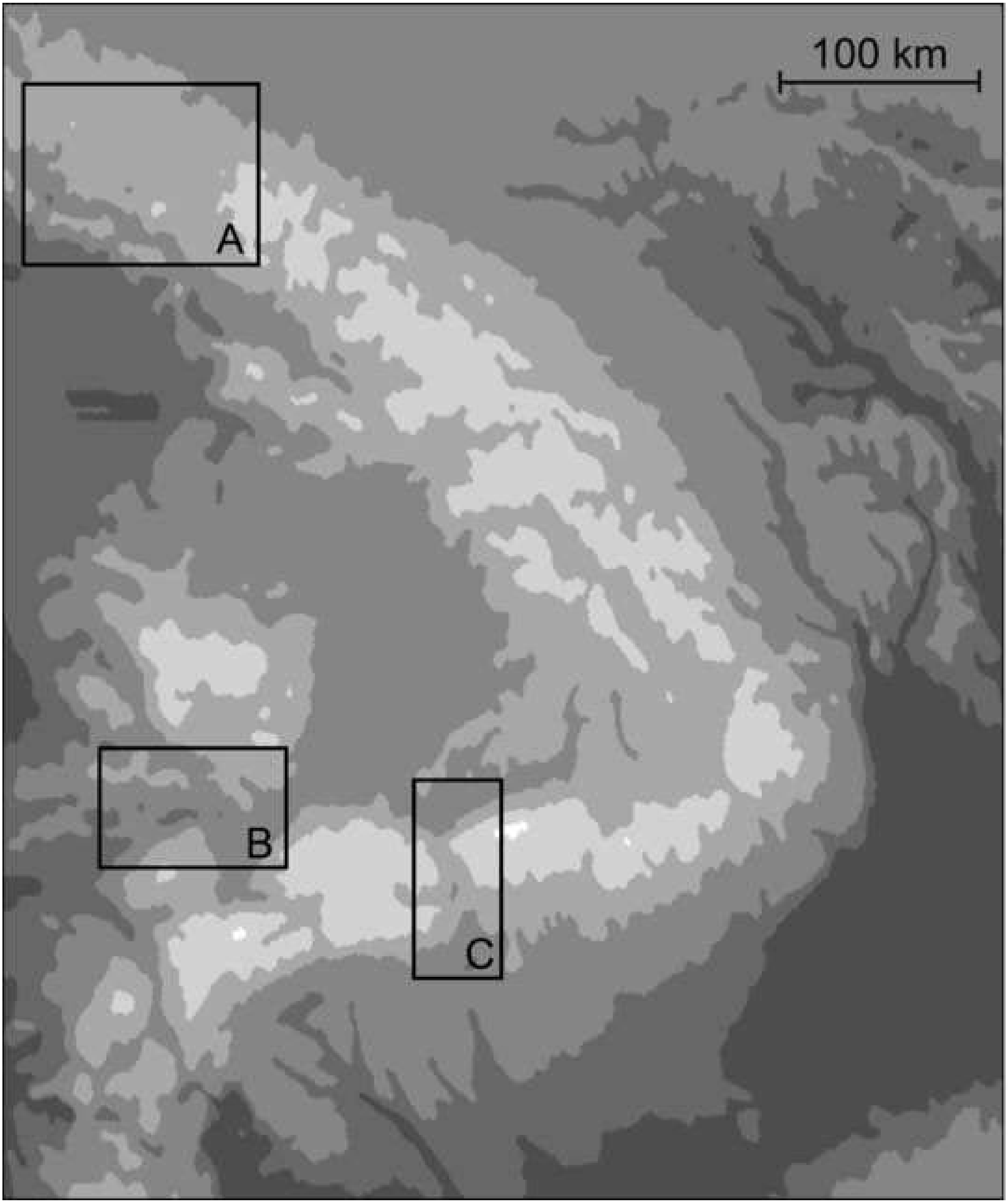


Figure 6

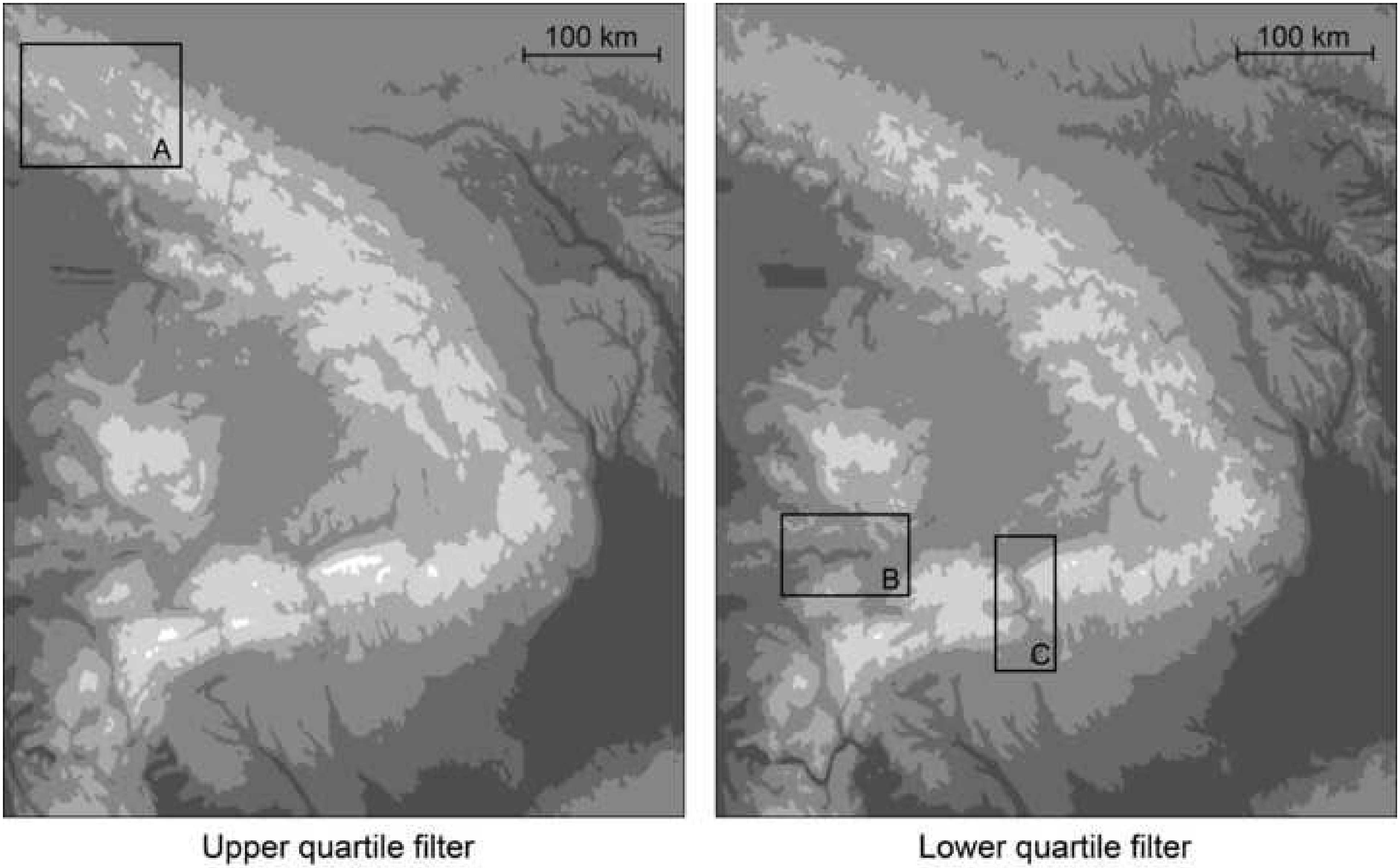

A
100 km
B
C
100 km
Upper quartile filter
Lower quartile filter

Figure 7

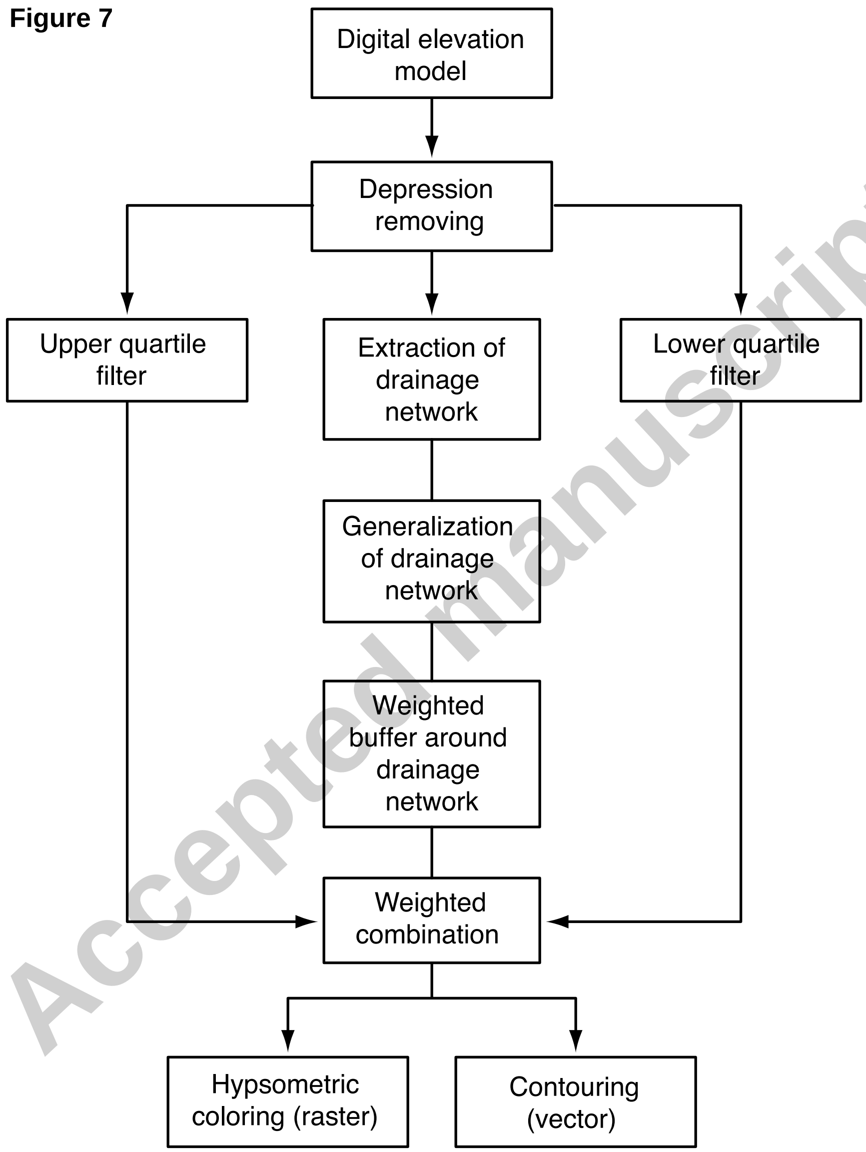
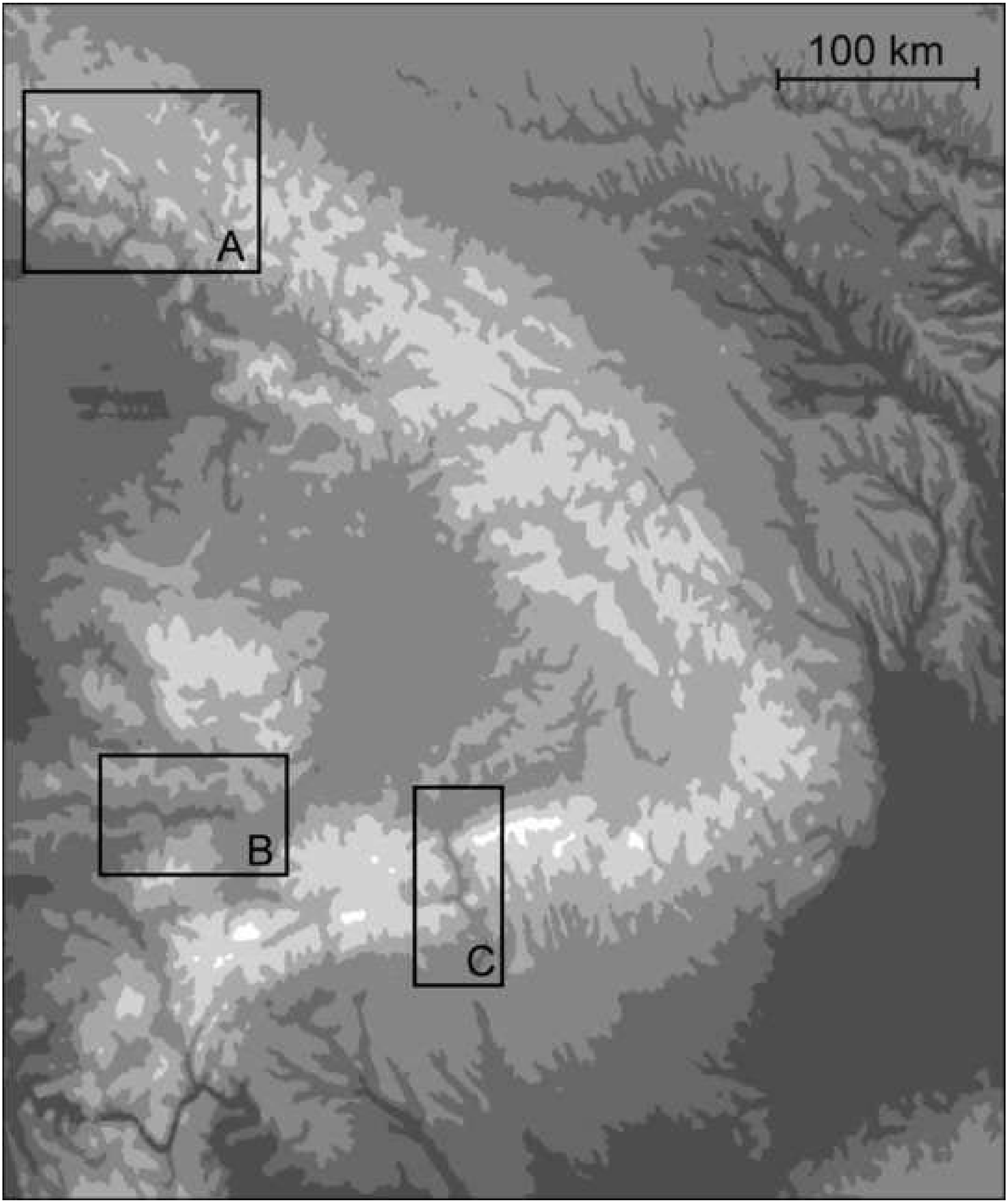

Digital elevation model
Depression removing
Upper quartile filter
Extraction of drainage network
Lower quartile filter
Generalization of drainage network
Weighted buffer around drainage network
Weighted combination
Hypsometric coloring (raster)
Contouring (vector)

Figure 8

Figure 9



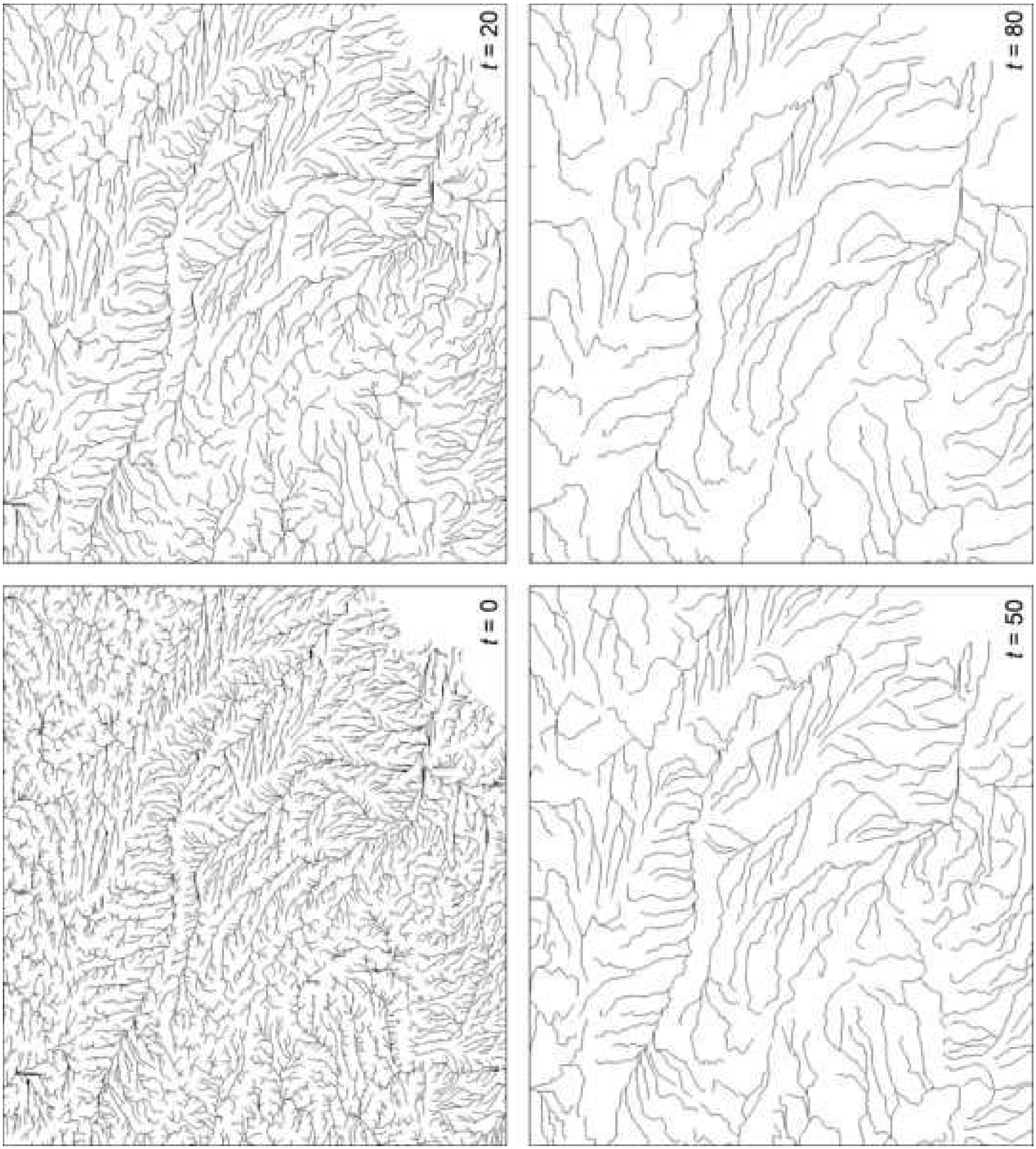


Figure 10

Figure 11

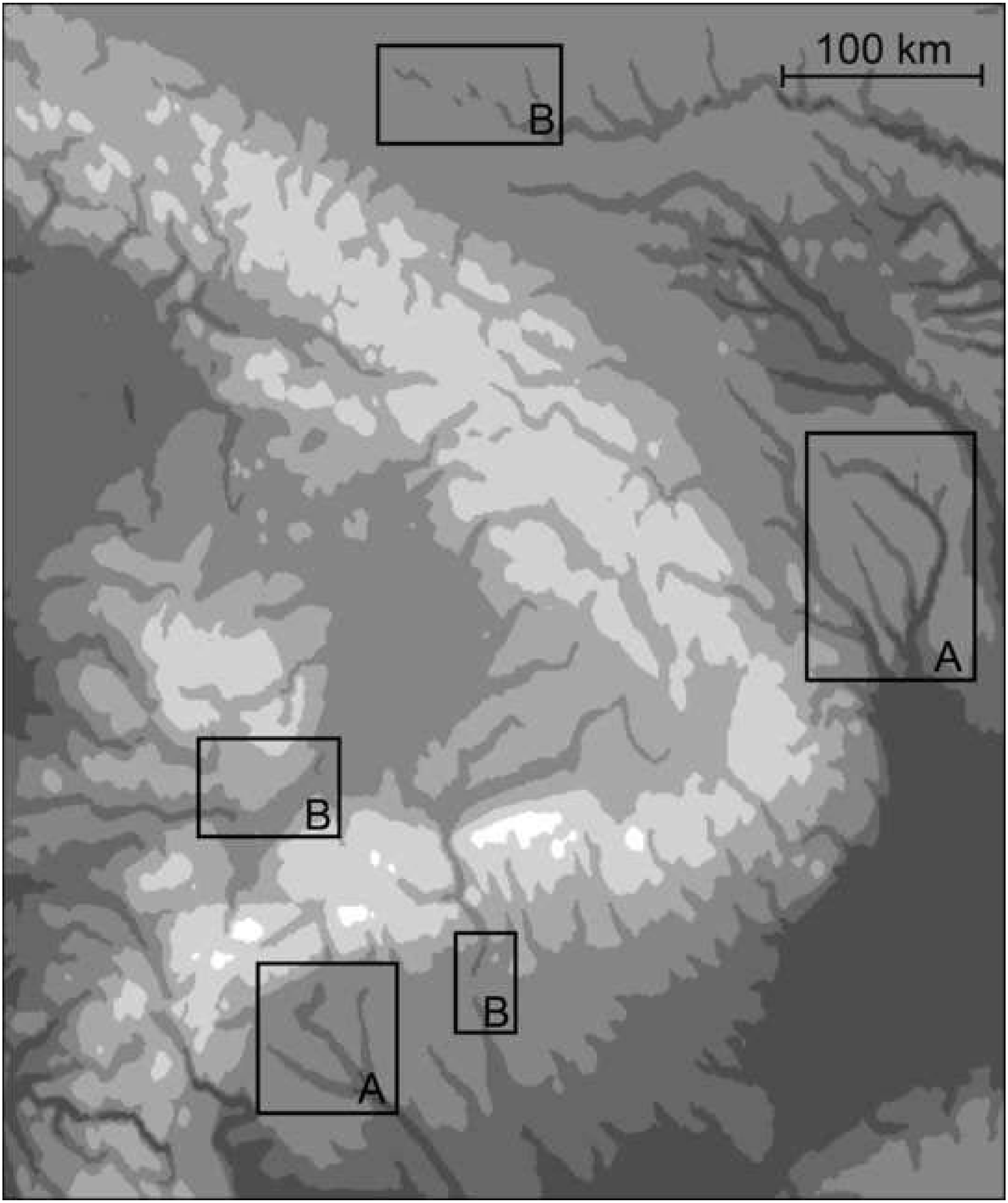
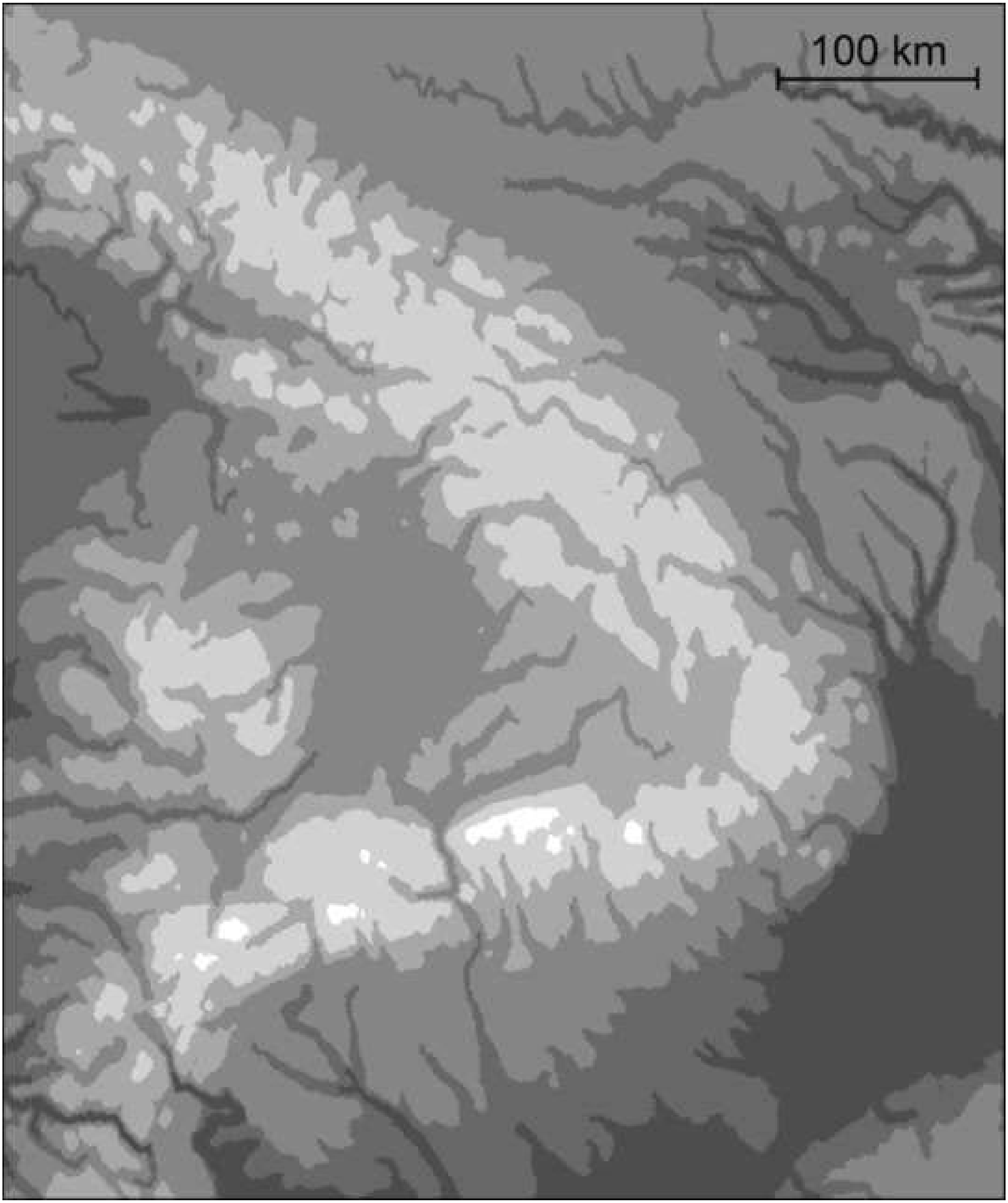


Figure 12



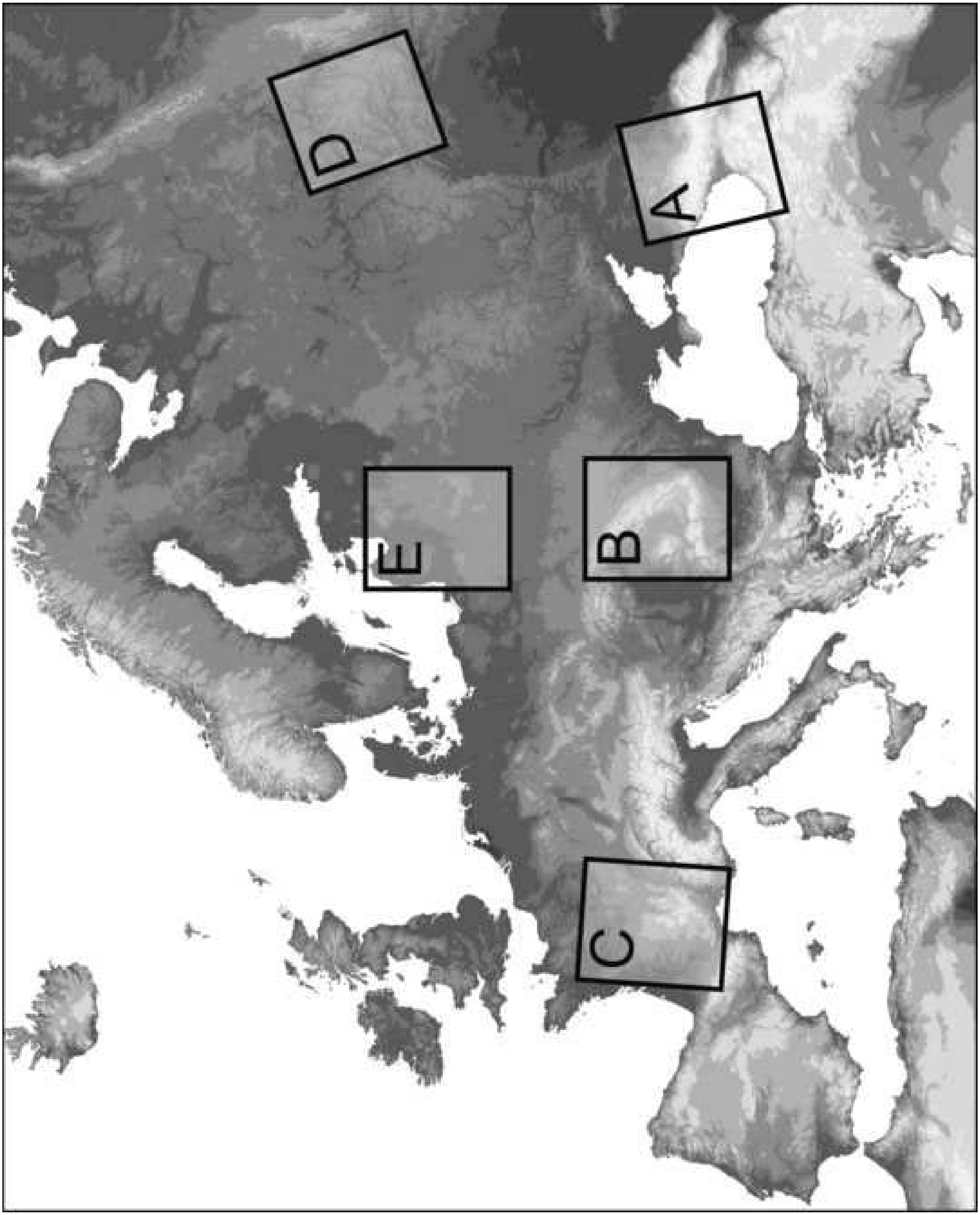
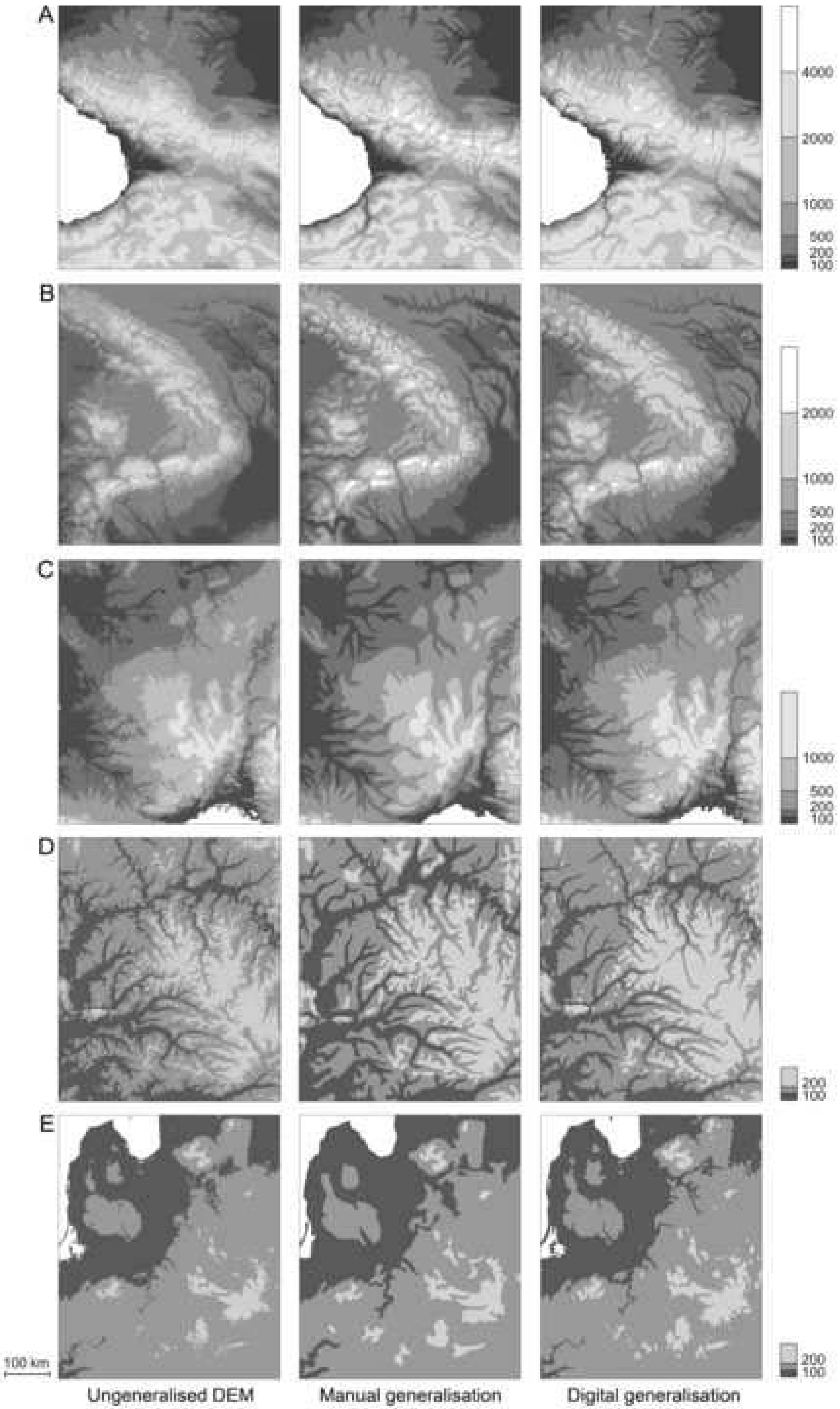


Figure 13

Figure 14


A
B
C
D
E
4000
2000
1000
500
200
100
2000
1000
500
200
100
1000
500
200
100
200
100
200
100
100 km
Ungeneralised DEM
Manual generalisation
Digital generalisation