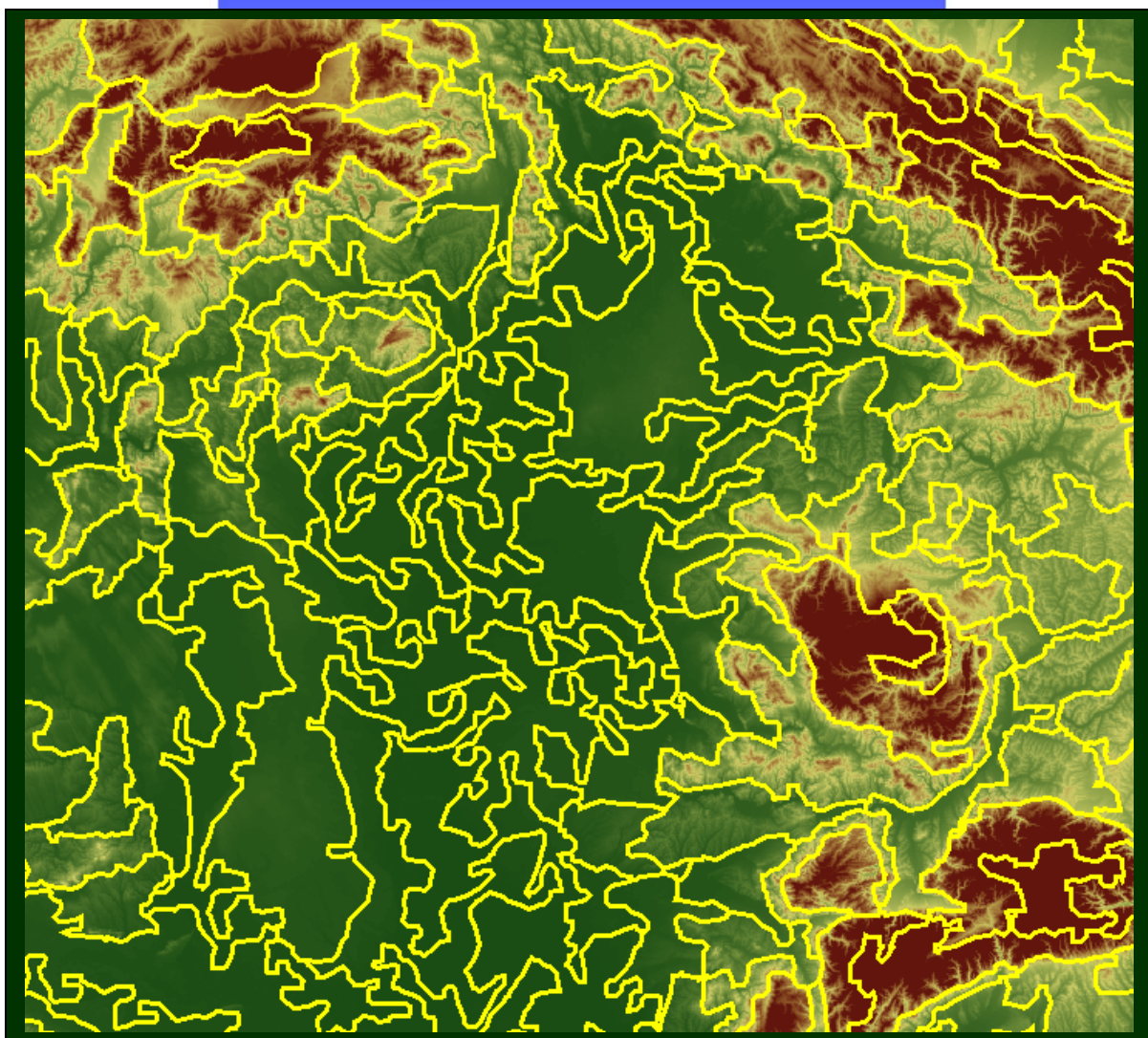# An SRTM-based procedure to delineate SOTER Terrain Units on 1:1 and 1:5 million scales

Endre Dobos
Joël Daroussin
Luca Montanarella

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An SRTM-based procedure to delineate SOTER Terrain Units on 1:1 and 1:5 million scales

Endre Dobos, Joël Daroussin and Luca Montanarella

Institute of Environment & Sustainability, Joint Research Centre, Ispra, Italy

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Table of contents

List of figures

List of tables

Preface

The users and developers of the SOTER database have accumulated many suggestions for improvement of the Soil and TERrain (SOTER) Procedure Manual since the last Manual was published in 1995. Meanwhile, new technology and data sources have become available for database development. Digital soil mapping technology advances very fast and provides many new quantitative approaches for surveyors of natural resources.

The work presented here has taken advantage from the emerging digital soil mapping technology and the 90 m resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) for the development of a quantitative procedure for SOTER Terrain Unit delineation. The target scales were 1:1 and 1:5 million. The procedure is based on the SOTER Manual specifications and is meant to be compatible with the datasets formally developed using the traditional way. Meanwhile, suggested changes regarding the Terrain Units delineation have already been implemented.

The results are published in this booklet in three major sections. The first part describes the procedure in a step-by-step manner, giving all the technical details needed to run the procedure. ArcInfo® geographical information system software (GIS) was used to execute the procedure. The commands have been recorded and are given for each section. The second part gives additional details on the Potential Drainage Density Index (PDD), its use, meaning and the procedure to derive it from the SRTM data. PDD was developed and used in this context to quantify terrain dissection, which is one of the four terrain variables used for SOTER Terrain Unit characterization. The last part is a complete list of command, an "ArcInfo® monitor file", which can be used to replicate the entire procedure.

The main reason for developing this procedure was to provide a tested methodology and to suggest it to be a potential standard for SOTER database development. Standard, quantitative methodology is strongly needed to avoid inconsistency among the input national datasets.

The development of a quantitative procedure for building physiographic units for the European SOTER database

Endre Dobos, Joël Daroussin, Luca Montanarella

European Commission, Joint Research Centre, Institute of Environment and Sustainability, Soil and Waste Unit, TP 280, 21020 Ispra (VA), Italy

1. Introduction

Soil data of various scales is needed to well manage our agricultural and environmental resources. On the European level soil information is used for crop monitoring, yield forecasting, agricultural planning, feasibility studies for rural development, natural hazards forecasting, such as floods and landslides or slowly acting processes such as erosion, acidification and other types of chemical, biological and physical degradation of soils. No appropriate scale soil database for the European Union had existed before the late eighties. The strong need for policy support has speed up the database compilation and resulted in the first version of the Soil Geographical Database of Eurasia at scale 1:1 million (SGDBE1M). Despite of its limitations, SGDBE1M is still among the few databases, which serve as a flagship in the development of the small scale spatial databases in Europe. The version 2.0 of SGDBE1M was published recently, in 2004. The refinement of the database and the extension of its geographic coverage to Eurasia and the Mediterranean Africa are in preparation.

A similar soil database would be needed for global scale forecasting, modelling and research. However the only available soil map with a global coverage is the 1 to 5 million scale FAO soil map of the world, which has been compiled from data collected up to the late seventies. Since the completion of the FAO soil map much new data have been documented and new approaches of mapping and database development have been developed. The lack of a standardized, compatible, credible soils database at appropriate scale is a major constraint to global modelling. Therefore, the SOTER (World SOil and TERrain Digital Database) project was initiated by the International Society of Soil Science (ISSS) in 1986 (ISSS, 1986). SOTER is intended to have a global coverage at 1:1 million scale (Batjes, 1990; ISRIC, 1993), which goal was later degraded to 1:5 million scale due to the lack of means. Other international organizations, such as the United Nations Environmental Programme (UNEP), Food and Agriculture Organization (FAO) of the United Nations and the International Soil Reference and Information Centre (ISRIC) joined this project and supported the idea of having a global scale soil and terrain database useful for a series of applications. A small international committee was appointed to develop a "universal map legend system" and to define a minimum necessary set of soil and terrain attributes suitable for compilation of a small-scale soil resources map. The database can provide information for a wide range of applications such as "crop suitability, soil degradation, forest productivity, global soil change, irrigation suitability, agro-ecological

5

zonation, and risk of drought" (ISRIC, 1993). Figure 1 shows the preparation status of SOTER in 2004.
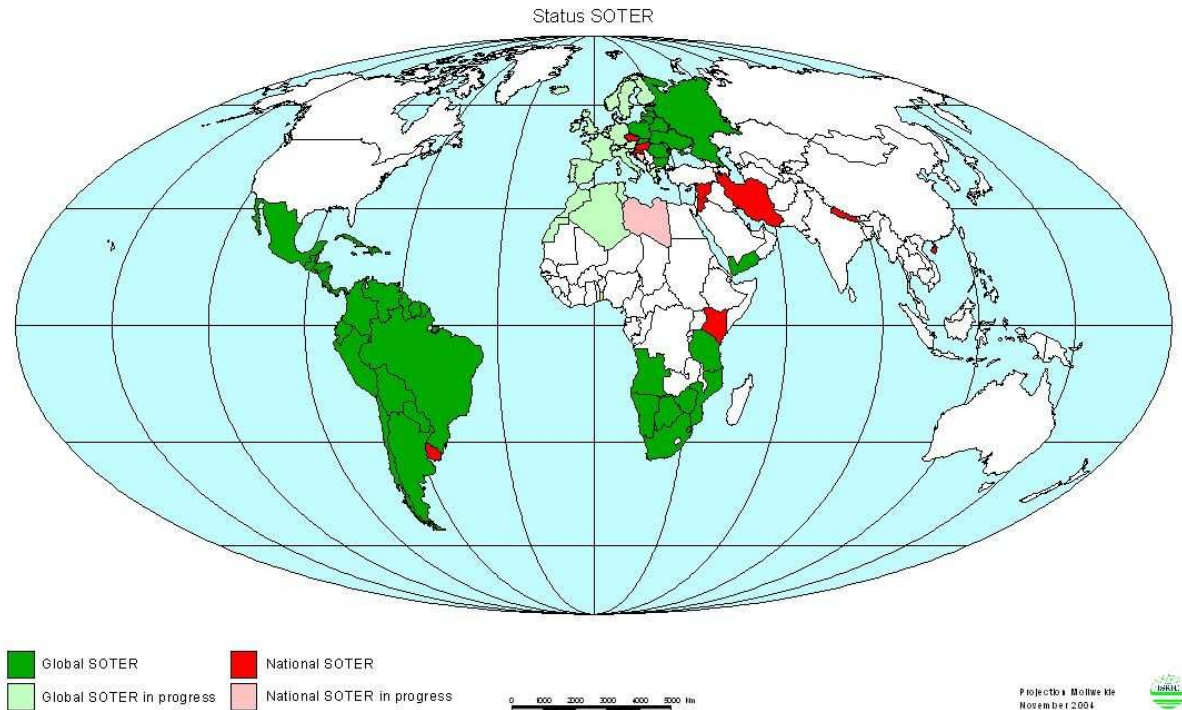
Figure 1: State of progress of the SOTER project in 2004 (from Vincent van Engelen, ISRIC).

As shown on Figure 1 the central and eastern part of Europe is completed within the SOVEUR project (Batjes and Bridges, 1997). The database is currently operational and has been used for assessing different land and soil degradation processes acting in the area. However, it still shows the most typical limitations of data inconsistency. The database was compiled from national databases provided and translated to the "SOTER language" by the national soil survey institutions. Differences in the interpretation of soil parameters are evident from the risk assessment maps (Figure 2). Almost all political borders are visible on the thematic map. Besides the variation in resolution and quality of the incorporated data, this artefact is most likely due to the differences in interpretation of numerous soil terms, and to the misplacement of the national soil variability on the global variability range. More appropriate quantification procedure for soil property characterization is needed to solve this problem.

The work has been started to prepare the SOTER database for the western part of Europe as well. The European Commission has agreed to complete the SOTER database for the EU countries at scale 1:5 million. The soil information for the EU SOTER map is taken from the SGDBE1M with an expert knowledge and decision rule controlled procedure developed by INRA Orléans. A preliminary version of the database has been completed by aggregating the existing SGDBE1M polygons. Unfortunately, the SGDBE1M polygon delineation does not follow the SOTER methodology. Thus the SOTER Unit delineation based on the aggregation of SGDBE1M polygons does not necessarily match SOTER criteria.

Emerging digital technology and high resolution digital terrain information, such as the digital elevation model (DEM) obtained by the Shuttle Radar Topography Mission (SRTM) (Farr

and Kolbrick, 2000), represent a great resource and potential for developing a quantitative procedure to replace the existing SOTER procedure. The main advantage of a quantitative procedure lies in the spatial and thematic consistency of the final product. Moreover it would speed up the work and decrease the amount of time and other resources needed to complete the database.

The existing SOTER procedure needs to be modified slightly, partly due to its natural evolution and partly because of the quantification of the criteria that were originally defined qualitatively. Dobos *et al*. (2004) did preliminary studies on the use of digital terrain and remotely sensed data for the SOTER Unit delineation. The results were promising and a program was launched to update and modify the SOTER procedure to incorporate digital elevation data in the delineation of the Terrain Units. This work is done jointly by the European Commission Joint Research Centre (EC JRC) - Soil and Waste Unit, ISRIC and FAO. A SOTER Procedure Modification (SPM) workshop was organized in Ispra, Italy, 21-22 of October 2004, to implement the changes that were agreed upon since the last published version of the manual and define the needs for future research to update the procedure and incorporate the newly emerging tools and data sources such as DEM data. Minutes of the meeting is available from the authors of this paper. The decision was taken that Europe would be the first pilot area and EU SOTER the database to test the new procedure.

This paper focuses on only part of the work within the SOTER Procedure Modification project, namely on the development of the quantitative, DEM based (using SRTM data) procedure to delineate SOTER Terrain Units at both 1:1 and 1:5 million scales. Terrain Units are defined only by their physiographic characteristics.

Figure 2: Degree and extent of acidification in central and eastern Europe derived from the SOVEUR database.

2. Materials and methods

2.1. The study area

The study area covers the countries of the European Union. However, in this paper as well as for the procedure development, a smaller pilot area was selected, namely the eastern half of the Carpathian basin (Figure 3). This site covers a great variety of soil, landscape, land use, climate, topography and vegetation types and was found to be ideal for developing and testing the procedure.

2.2. The data

The Shuttle Radar Topography Mission (SRTM) global elevation data covers almost 80 percent of the globe, almost all terrestrial land surfaces. Its coverage extends between 60˚ north and 56˚ south latitudes. SRTM is a joint project between the National Aeronautics and Space Administration (NASA) and the Department of Defence's National Geospatial - Intelligence

Agency (NGA) to produce a near global digital elevation data coverage at a relatively high spatial resolution. Farr and Kolbrick (2000) describe the data capturing and processing procedure. The data is handled and distributed by the United States Geological Survey and can be downloaded from their ftp site (ftp://edcsgs9.cr.usgs.gov/pub/data/srtm/).

The basic product has a 1 arc second resolution, but it is publicly available for the US territories only or under agreement with the NGA. This data was resampled to 3-arc seconds resolution by averaging a 3 by 3 cells area. This 3 arc seconds resolution data is used and suggested for SOTER studies to keep the consistency of the procedure over all regions of the world. The metric, projected, resolution of this data at the equator is approximately 90 meters. The data has gaps, i.e. areas with no information (NODATA), where water bodies or mountains prevented the backscattering of the radar beams, thus providing insufficient signal to process. These voids can limit its use, e.g. for hydrological modelling. The Consultative Group for International Agricultural Research - Consortium for Spatial Information (CGIAR-CSI) has produced a post-processed version of the 3 arc second data using a hole-filling algorithm to provide continuous surfaces. The procedure is described by Jarvis *et al*. (2004). The algorithm vectorizes the data to produce contours with 10 meters vertical intervals and than uses the ArcInfo® TOPOGRID tool (Hutchinson 1988, 1989) to produce a hydrologically sound DEM. Data from this DEM is taken to fill the "*no data*" area of the original SRTM data. Jarvis has reported that most macro-scale features has been captured by the algorithm and no significant difference which can alter the use of the data was found between the processed SRTM and the DEM derived from cartographic map. The hole-filled data can be downloaded from the CGIAR-CSI website: http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp. It was used in this project.

The SRTM data was then projected from WGS84 geographical latitude/longitude coordinates to the standard Lambert Azimuthal Equal Area projection to make the metric calculations possible.

A snapshot of an example 3-dimensional view of SRTM elevation data over the Carpathian basin is shown on Figure 3.

Before the SRTM data could be used, the input DEM had to be hydrologically corrected. Sinks that are due to errors in the data and the micro-scale natural sinks – which, at that scale, appear as noise – had to be filled, while the meso- and macro-scale natural variability of the area were kept. Filling all sinks may result in removing all the natural variability, including real geomorphologic units such as depressions or basins, which need to be kept for meaningful landscape characterisation on plain areas. Figure 4 shows an example of such situations occurring on the northern half of the Hungarian Great Plain. The image on the left shows the original, unfilled SRTM data, representing elevations between 87 and 172 meters. The image to the right shows the same area after using the FILL command within the ArcInfo® GRID module. Notice how all variability has been eliminated and the entire Great Plain was filled up to the elevation of 90 meters. Using this second image would be useless for terrain characterisation of the area. According to our experience in using SRTM data, a limit of 20 meters has to be set as a maximum sink depth to be filled. This limit was suggested here as well.

9
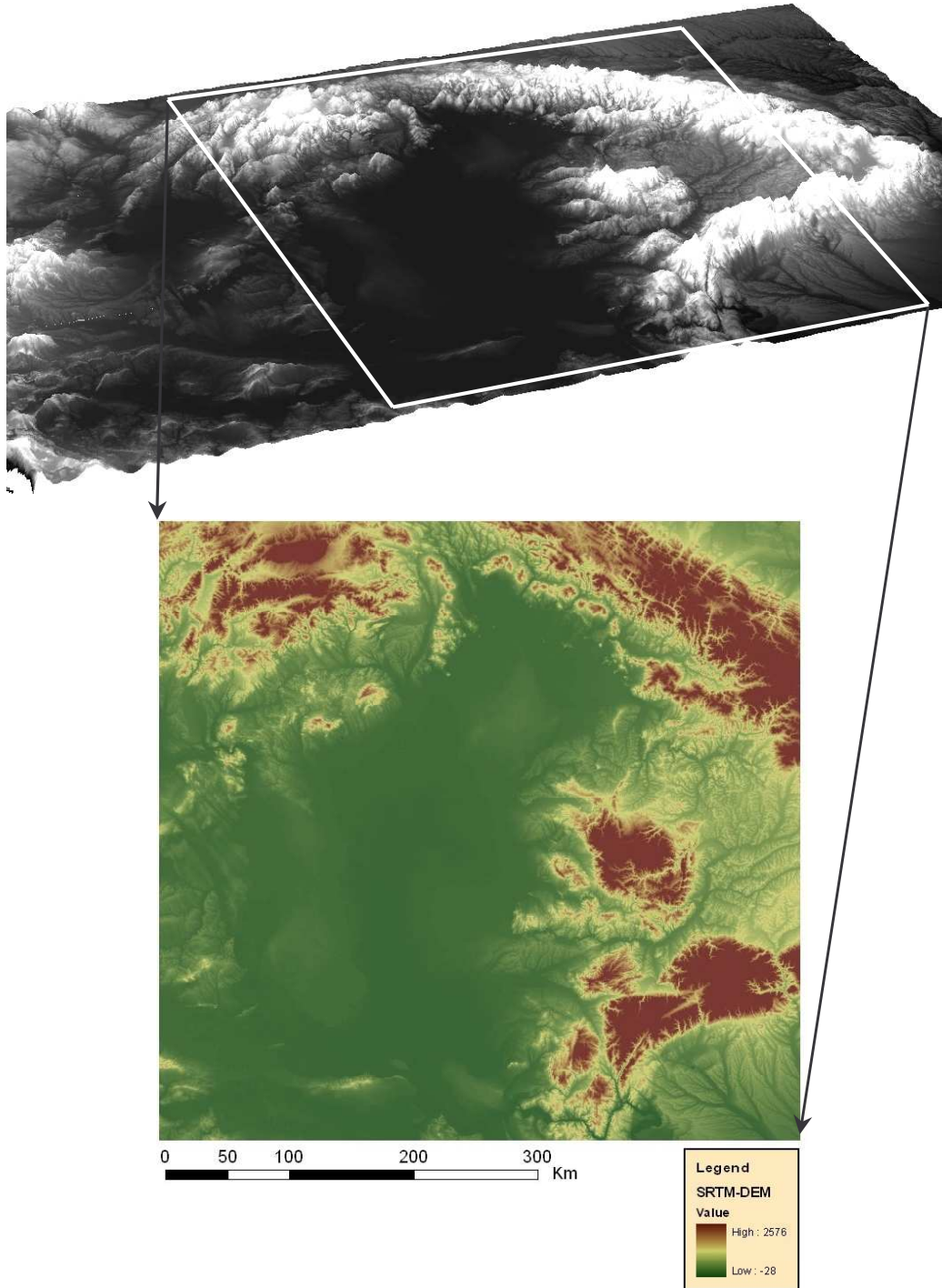
Figure 3: A 3D snapshot of SRTM elevation data over the Carpathian basin. The white box and bottom image show the pilot area.

The ArcInfo® command used for filling sinks:
FILL dem demfill SINK 20
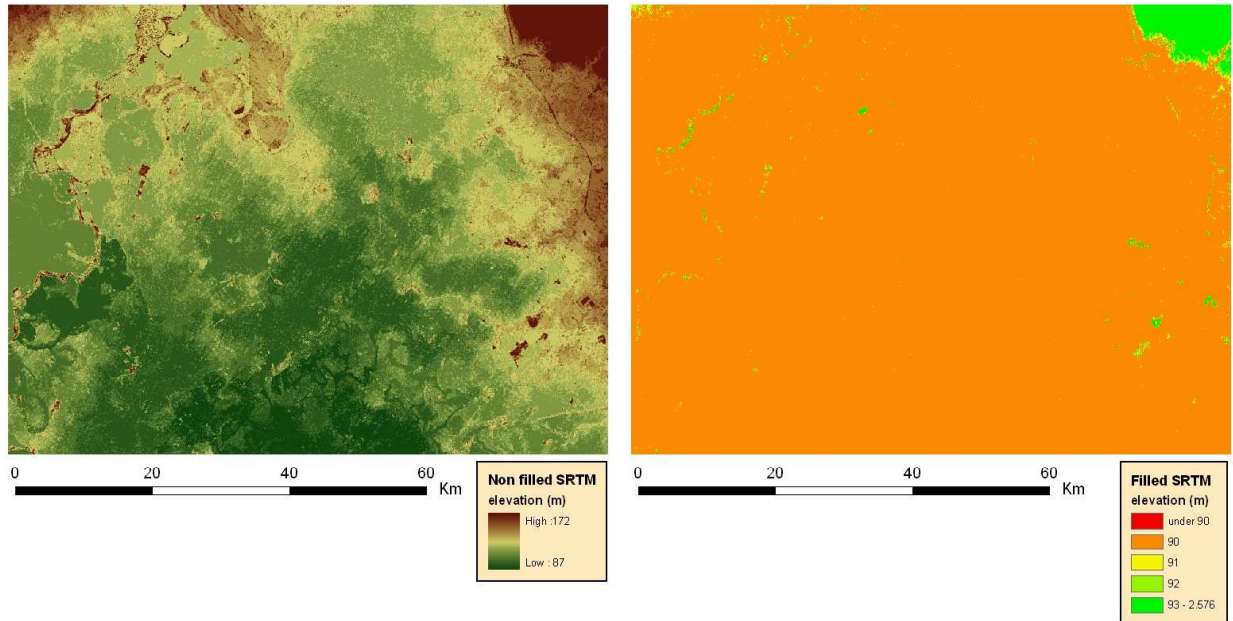
Figure 4: SRTM images of the northern half of the Hungarian Great Plain. The left image shows the area before filling the sinks, while the right one shows the same DEM once filled

2.3. Methods

2.3.1. SOTER Terrain Unit delineation

SOTER Unit delineation is based on two primary soil formation phenomena: terrain and lithology. Each SOTER Unit represents a unique combination of terrain and soil characteristics. The two major differentiating criteria are applied in a step-by-step manner, leading to a more detailed identification of the land area under consideration. Physiography is the first differentiating criterion to be used to characterize a SOTER Unit. The term physiography is used in this context as the description of the landforms on the Earth's surface. It can be best described as identifying and quantifying the major landforms, on the basis of the dominant gradient of their slopes and their relief intensity. The use of these variables, in combination with a hypsometric (absolute elevation above sea level) classification and a factor characterizing the degree of dissection, can make a broad subdivision of an area and delineate it on the map. Further subdivision of the SOTER Unit according to the lithology (parent material) needs to be done to complete the delineation procedure.

Until recently, manual methods were used to delineate SOTER Units. The availability of DEM makes it feasible to use a quantitative approach. Worstell (2000) has proposed an approach using DEM for SOTER Terrain Unit delineation based on Edwin Hammond's (1954) landform classification methods. Worstell has adapted and modified his methods to create a quantitative procedure to classify landforms on a regional scale.

A new, quantitative method for creating a SOTER database has been demonstrated by Dobos *et al.* (2004). They used the 1 km resolution SRTM30 data as the base DEM. Although the procedures were promising, they suggested more research and quality check on the results.

11

The aim of the present study was to develop a quantitative method to derive terrain classes that match the criteria of the SOTER Manual of Procedure. According to the manual, four terrain attributes are used to define the SOTER Terrain Unit: hypsometry (elevation), slope percentage, relief intensity and dissection. These attributes were derived from the digital elevation model by translating and reformatting the class characteristics. The four layers are combined to produce the complex landform classification. This combined layer was then vectorized, and finally generalized to achieve the polygon size limit appropriate for the target scale of the database to be produced.

The class limits of these attributes are defined more or less quantitatively in chapter 6 of the Manual, "Attribute coding", except for the dissection for which only qualitative definitions are given. Units for some attributes had to be modified slightly due to technical considerations. Changes in the class borders were implemented as well, which have been proposed and agreed upon in the SOTER Procedure Modification workshop. The dissection class limits were derived from the PDD layers (Dobos *et al*., 2000) through an empirical approach.

SRTM DEM - based Procedure
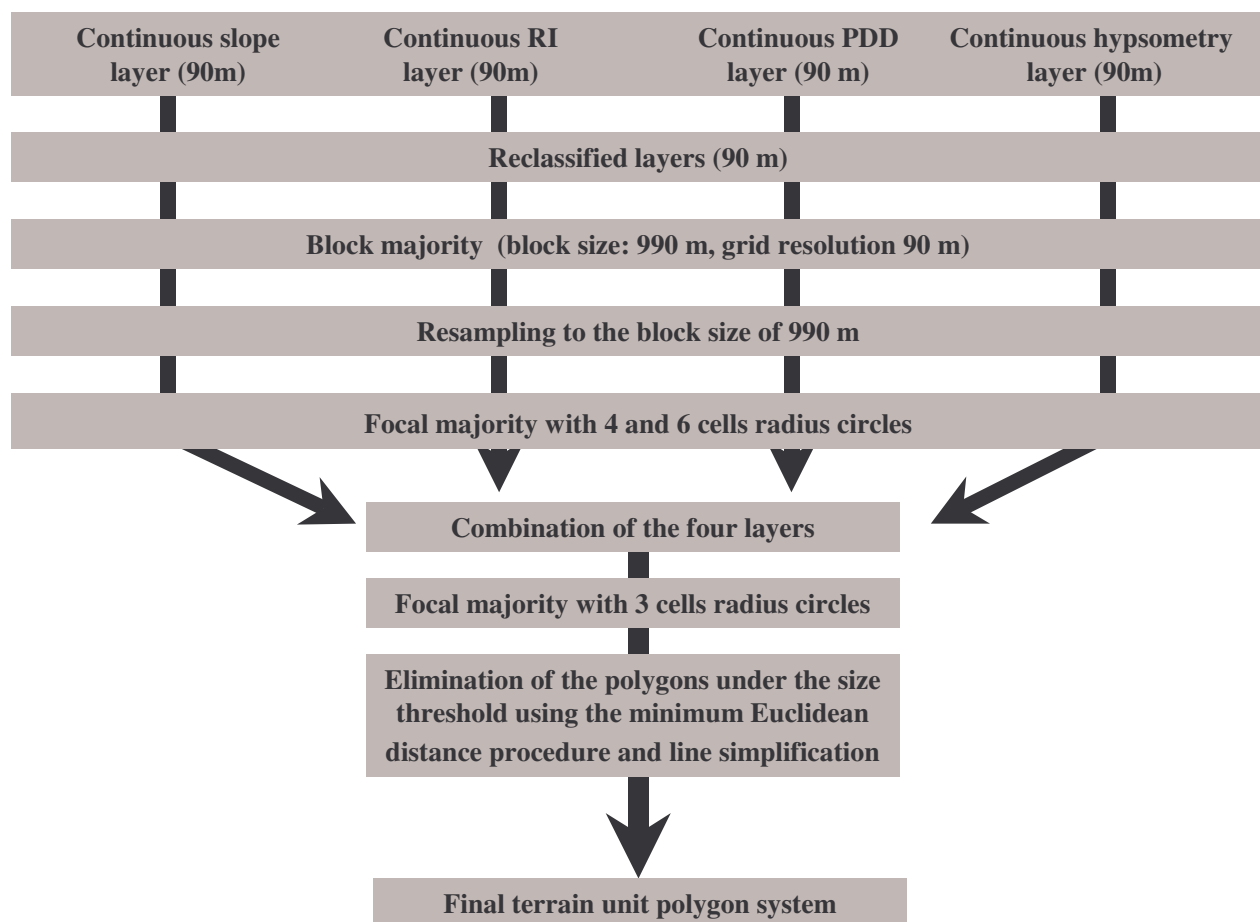
Figure 5: Flowchart of the Terrain Unit delineation.

Coarse resolution DEM tends to generalize the land surface and eliminate the micro- and meso-scale features of the surface, drastically decreasing the slope and relief values of the area (Wilson *et al*., 2000). Therefore, a fine resolution DEM (SRTM) with 90 m spatial resolution at the equator was used to maintain the higher scale landscape elements and to derive the terrain descriptor values for the area. The resulting variables show much more detail than what the targeted scales are capable of handling. Thus, a generalization and aggregation procedure was used to obtain the appropriate resolution.

The classifications for the four terrain layers are described in the four sections below. Figure 5 shows the flowchart of the work. ArcInfo[®] geographical information system software and its GRID raster analysis module were used to achieve the work.

2.3.2. *The creation of the four thematic layers*

2.3.2.1. *Slope*

The slope layer was derived from the SRTM data using the slope function available from the ArcInfo[®] GRID module. This function uses the average maximum technique (Burrough, 1986, see also the software online help). It calculates the slope for a fitted plane surface on a 3 by 3 cells neighbourhood centred on the processing cell (marked as "e" in Figure 6) as follows:
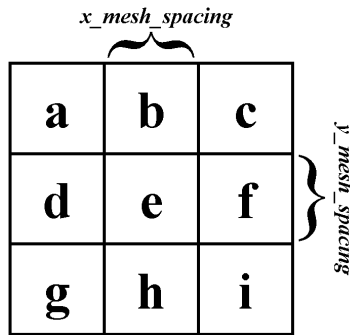
Figure 6: An example of a 3 by 3 cells moving window. Cell "e" is the centre – or processing – cell. Other cells are the neighbouring cells.

$$rise\_run = \sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2}$$

$$degree\_slope = \arctan(rise\_run) * 57.29578$$

where the deltas (dx, dy and dz) are calculated using a 3 by 3 cells moving window as follows:

$$\frac{dz}{dx} = \frac{(a + 2d + g) - (c + 2f + i)}{8 * x\_mesh\_spacing}$$

13

$$\frac{dz}{dy} = \frac{(a+2b+c)-(g+2h+i)}{8*y\_mesh\_spacing}$$

where [a] to [i] are the altitude values of cells **a** to **i**, and [x_mesh_spacing] and [y_mesh_spacing] are the distances between cell centres in the x and y directions respectively. Altitudes and distances are expressed in the same measurement unit.

The SOTER Procedure Modification workshop has suggested a new classification scheme for the slopes which is shown in Table 1.

Table 1: The slope classification as suggested by the SOTER Procedure Modification workshop.

Slope class	Range of slope percentage
1	0 - 2
2	> 2 - 5
3	> 5 - 10
4	> 10 - 15
5	> 15 - 30
6	> 30 - 45
7	Above 45

The use of SLOPE function resulted in a continuous slope layer, which was reclassified according to the SOTER classes in Table 1. This kind of classification rarely results in distinct borders between the classes, necessary for defining polygons of practical size. It gives too much spatial detail, which cannot be represented at the target scale ("salt and pepper" effect). Therefore, adequate filters have to be used to derive the slope layer with homogenous pattern of slope classes and the resolution has to be degraded to reach the spatial detail needed for the target scale.

The ArcInfo® commands used for this section:
slope = SLOPE (demfill, PERCENTRISE)
slopeclass = RECLASS (slope, slopeclass.txt)

2.3.2.2. *Raster-based generalization procedure*

The main steps of the generalization procedure are shown in Figure 7 and Figure 8. The appropriate spatial resolution of the grid for a 1:1 million scale target database is around 1x1 km (McBratney *et al.*, 2004). Two options were considered for degrading the resolution, (i) averaging the cell values within 1 km² area or, (ii) taking the majority class and assigning it to the spatially degraded cell (blocks). It was agreed, that the majority class of the area characterises the landscape better than the average value. Therefore, the blocking approach was applied by means of the ArcInfo® GRID module BLOCKMAJORITY function to define the majority class within a square shape area with the size of 11 by 11 cells (990 m by 990 m). The resulting grid remains with the original 90 m resolution. Therefore it was then resampled to the target resolution of 990 meters, which is believed to be appropriate for the target 1:1 million scale.
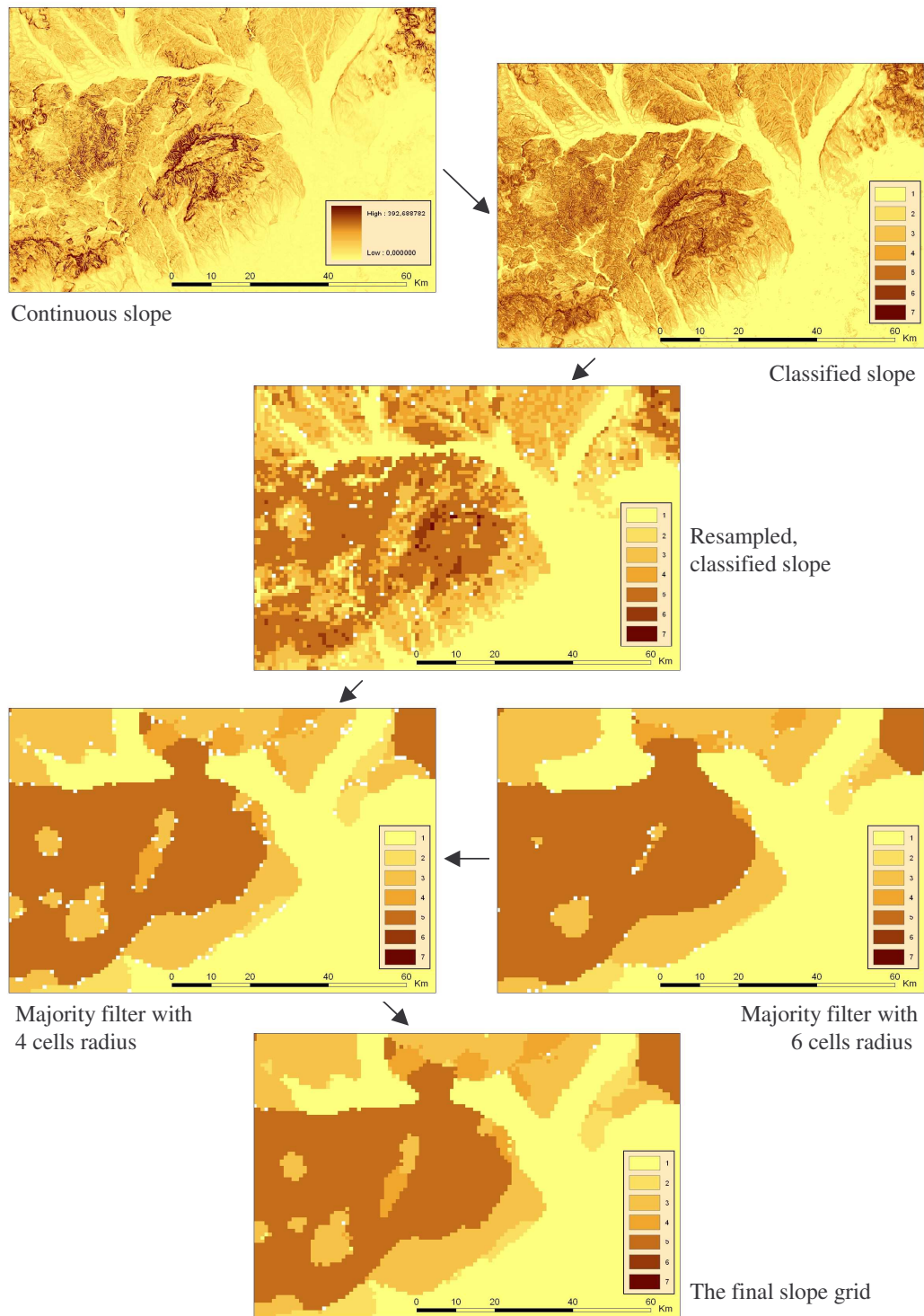
Figure 7: Flowchart explaining the creation of the slope grid illustrated with an example from the Bükk-mountain, Hungary. Table 1 provides the corresponding slope classes.

The resulting grid still had some salt and pepper effect, having a mixture of stand-alone cells or small contiguous areas, especially on the transition zones between the classes. This phenomenon represents a significant problem when meaningful polygons are to be drawn with a minimum polygon-size requirement. To overcome this problem, a filter was applied to that grid layer by using the FOCALMAJORITY function with a 4 cells radius circle. The function takes the most frequently occurring class within the specified neighbourhood and assigns it to the centre cell of the moving window. This relatively small neighbourhood was chosen not to over-generalize the landscape, while having enough area to smooth the grid to the required level. In case of equal representation of two or more classes within the specified neighbourhood, a "*no data*" value is given to the centre cell, which has to be filled with meaningful information. To achieve this, the same filter was used again but with a bigger, 6 cells radius, circle, and the "*no data*" cells in the previous step were replaced with values from this grid layer. Applying these two steps creates patches having sizes appropriate at that target scale.

The ArcInfo® commands used for this section:
/* BLOCKING AND RESAMPLING:
slopeblock990 = BLOCKMAJORITY (slopeclass, RECTANGLE, 11, 11)
slopeclass990 = RESAMPLE (slopeblock990, 990)

/* FILTERING:
slope990filt4 = FOCALMAJORITY (slopeclass990, CIRCLE, 4)
slope990filt6 = FOCALMAJORITY (slopeclass990, CIRCLE, 6)
slope990 = CON (ISNULL (slope990filt4), slope990filt6, slope990filt4)

2.3.2.3. *Relief Intensity (RI)*

The Relief Intensity (RI) is one of the most significant discriminating terrain factors in the SOTER Procedure. RI is defined as the range of altitudes within a specified distance from each cell, i.e. the difference in altitude between the highest and lowest points within that distance. It is used in three different places in the procedure: in the major landform description, in the hypsometry characterisation and finally, in the dissection characterisation. Unfortunately, different units - expressed as *m/km*, *m/2km* and *m/slope unit* respectively - and thresholds have been used within the three sections. These units are difficult to interpret and difficult to handle consistently within a unified RI layer. That is why the SOTER Procedure Modification workshop came up with a simplified classification (Table 2) and introduced a new unit for measuring RI, which is now expressed in *m/[area of a 1 km diameter circle]*. For practical reasons in the implementation of the method, the 1 km diameter is approximated with a 990 m diameter because, when using 90 m resolution projected SRTM data, it can thus be expressed simply with a 5 cells radius circle (5 cells radius = 11 cells diameter = 990 metres diameter circle).
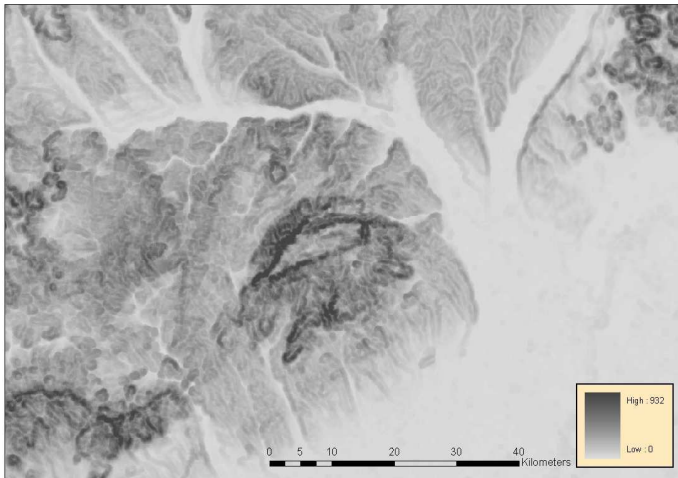
Continuous relief intensity map
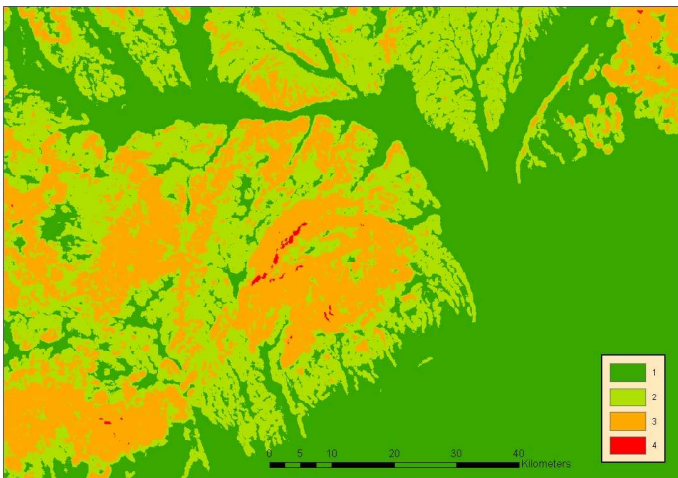
Classified relief intensity map
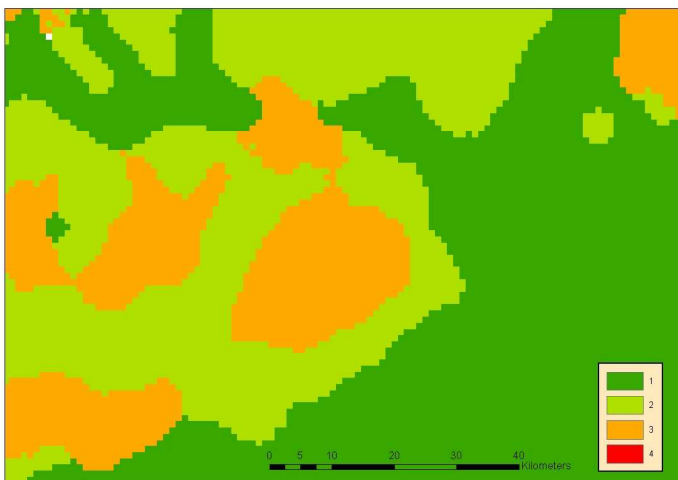
Classified and resampled
relief intensity map

Figure 8: The Relief Intensity layers illustrated with an example from the Bükk-mountain,
Hungary. Table 2 provides the corresponding RI classes.

17

The algorithm defines a circle shape neighbourhood with a radius of 5 cells and identifies the highest and the lowest points within that area. The difference between these two points is assigned to the centre cell of the moving processing window as an RI value. Within the ArcInfo® GRID module, the procedure is implemented using the FOCALRANGE function.

The rest of the procedure was basically the same as in the one used for deriving the slope layer. High resolution, 90 m SRTM data was used to create the original RI layer, which was later classified according to the classes listed in Table 2. Then this classified image was generalized following the generalization procedure described above in section 2.3.2.2.

Table 2: The Relief Intensity classification as suggested by the SOTER Procedure Modification workshop.

Relief Intensity class	Altitude range in meters within a 990 m diameter circle
1	0 - 50
2	> 50 - 100
3	> 100 - 300
4	Above 300

The ArcInfo® commands used for this section:
ri = FOCALRANGE(demfill, CIRCLE, 5)
riclass = RECLASS (ri, riclass.txt)

2.3.2.4. *Dissection (PDD)*

The degree of dissection is difficult to quantify with traditional methods (ISRIC, 1993). The use of DEM makes it feasible to derive an artificial drainage/valley network, which characterizes the landscape dissection. Dobos *et al*. (2000) developed an index called the Potential Drainage Density (PDD) and a function to compute the PDD. The function derives a drainage network from the DEM and measures the network's density within a predefined sized neighbourhood. The nature of – and the procedure for creating – the PDD layer are described in this book among the technical notes (Dobos and Daroussin: The derivation of the Potential Drainage Density Index (PDD)).

The data was processed in two steps. In the first step, a DEM-based drainage network was derived by thresholding flow-accumulation values. Cells having a flow-accumulation value higher than this threshold were considered as drainage ways. These drainage cells were assigned a value of 1, while all other cells were set to "*no data*". In the second step, a size for a moving window was selected, and a count of the drainage-way cells within the window was assigned to the centre cell. The result is the PDD value. The higher the PDD value, the more dissected the terrain.

The procedure suggested here requires three parameters to be set: (1) the flow accumulation threshold for the drainage network derivation, (2) the radius of the circle for the

counting window and (3) the class limits for the reclassification of the continuous PDD image. No decisions were taken at the SPM workshop regarding these settings. They were left open for further testing and adjustment.
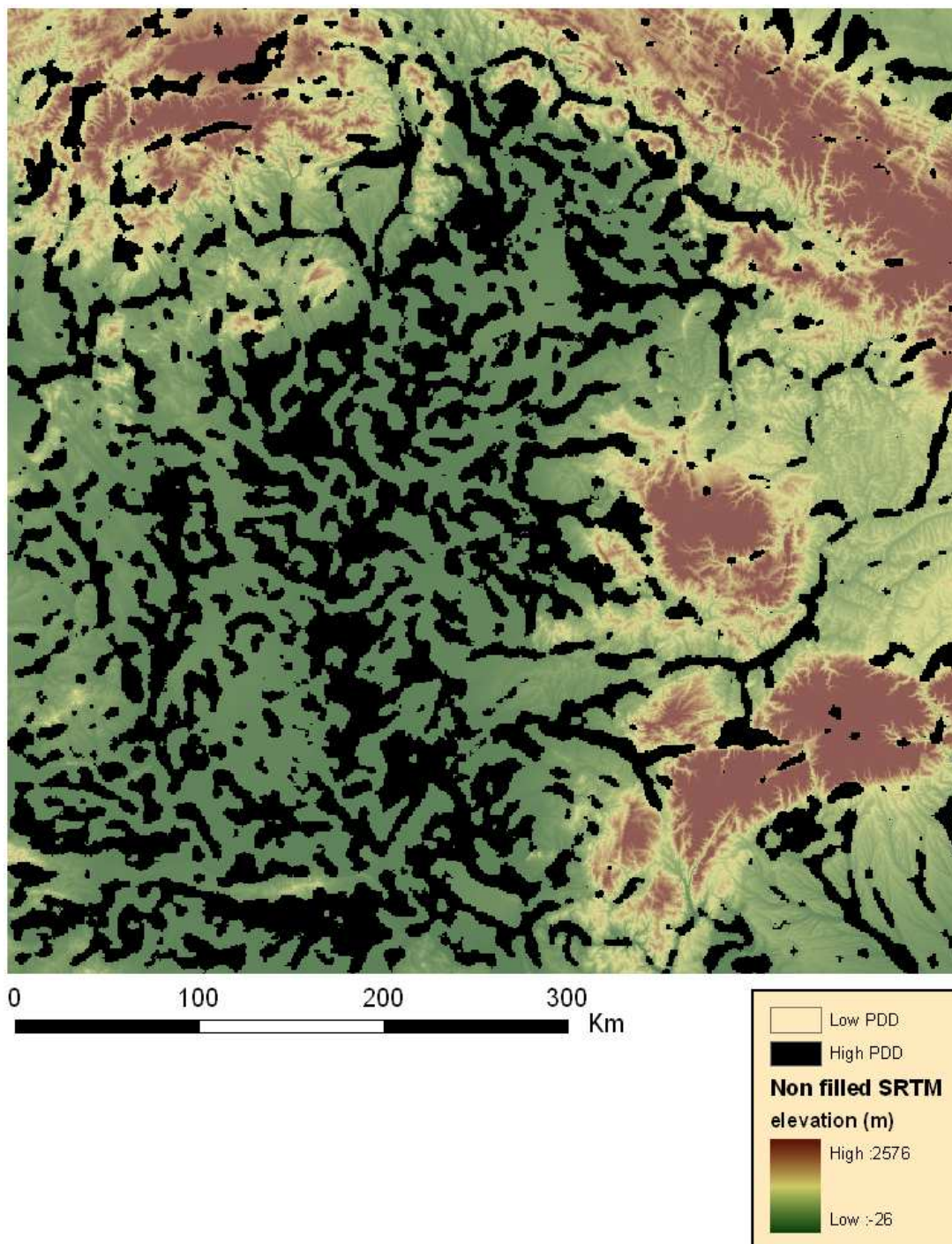
Figure 9: The PDD layer derived from the SRTM data in the Hungarian Great Plain and part of the Carpathians. The black areas represent the high PDD value class.

Choosing a flow accumulation threshold to build the drainage network:

The threshold value was set to 100, which is a commonly accepted value for drainage density derivation. In the case of the SRTM data, it translates to approximately a 1 km^2 catchment's area for a drainage line to start. The advantage of this value is that the resulting drainage system has a quite dense coverage, highlighting all the reasonable sized features of the landscape. Lower values create a very dense network with too many details, while higher thresholds decrease the pattern density, thus missing some necessary details.

Choosing a radius for the circle to count drainage cells:

The radius was set to 20. This is also an empirical choice. Several sizes were tested. The rule of thumb is that a radius that is too small is not able to deliver meaningful information about the general landscape. The resulting images show buffer-like zones along the drainage lines with relatively big portions of the image having "*no data*". Choosing a radius that is too large tends to over-generalize the image, there again masking general landscape characteristics. The optimal choice is the smallest circle, which is still big enough to always pick up at least one drainage cell. After several trials and errors, the radius value of 20 was found to be appropriate for the drainage network derived from the SRTM data using the flow-accumulation threshold value of 100.

Choosing class limits for the reclassification of the continuous PDD image:

The dissection measurement unit as defined in the "Manual of Procedure" is the length of permanent and seasonal streams and rivers within a 1 km^2 neighbourhood. Three dissection classes are distinguished: 0-10, 10-25, and above 25 km/km^2. In this study, using these class limits would have been meaningless because the approach is different in the sense that we use "potential" drainage lines *versus* actual ones. In the digital procedure, only two classes were defined with value ranges as given in Table 3.

Table 3: The PDD class ranges.

Class	PDD value range
1: less dissected areas, convex surfaces	0-90
2: more dissected areas or depressions, concave surfaces	Above 90

The ArcInfo® commands used for this section:
flowdir = FLOWDIRECTION(demfill)
flowacc = FLOWACCUMULATION(flowdir)
drainage = CON(flowacc > 100, 1)
pdd = FOCALSUM(drainage, CIRCLE, 20)
pddclass = RECLASS(pdd, pddclass.txt)

The procedure then followed the same line as for the other layers by applying the generalization and filtering procedure described above for slope in order to derive the final image (Figure 9).
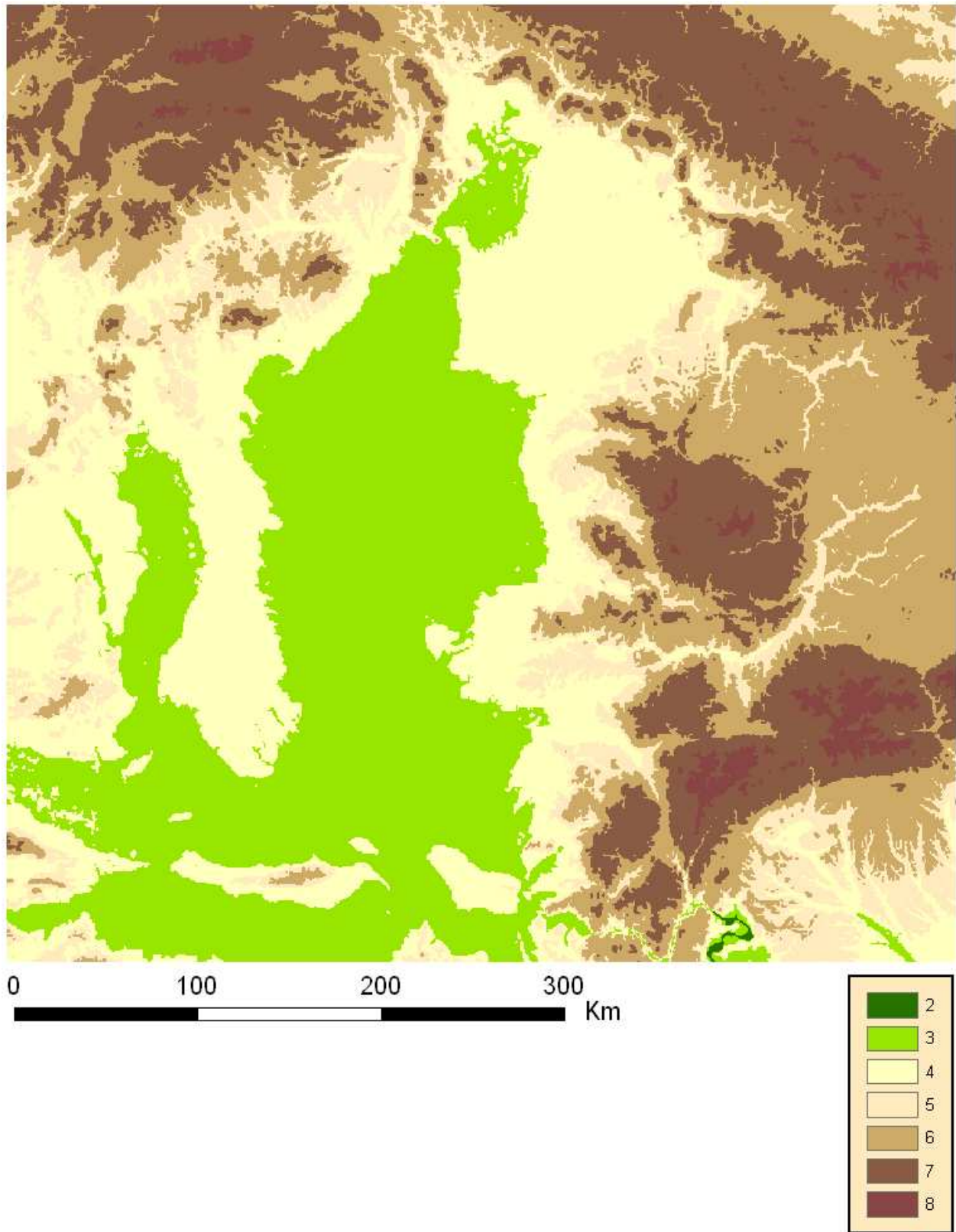
Figure 10: The hypsometry layer derived from the SRTM data in the Hungarian Great Plain and part of the Carpathians. Table 4 provides the corresponding hypsometry classes.

2.3.2.5. *Hypsometry (elevation)*

The original SOTER Procedure Manual suggests a two steps procedure for elevation classification. The first step divides the area into three general relief types, namely (i) the level lands, (ii) the sloping lands and (iii) the steep sloping lands. The second step further divides each of these three types into elevation subclasses but using a different classification scheme for each type. This two steps classification system was simplified by the SPM workshop and a new one was introduced (Table 4) which was used here as well.

After the SRTM image was reclassified using the classes in Table 4, it followed the same generalization and filtering procedure as the other layers to derive the final hypsometry image (Figure 10).

Table 4: The Hypsometry classes suggested by the SPM workshop.

Hypsometry class	Elevation range (meters above sea level)
1	Up to 10
2	> 10 - 50
3	> 50 - 100
4	> 100 - 200
5	> 200 - 300
6	> 300 - 600
7	> 600 - 1500
8	> 1500 - 3000
9	> 3000 - 5000
10	Above 5000

The ArcInfo® command used for this section:
hypsclass = RECLASS (demfill, hypsclass.txt)

2.3.2.6. *Database compilation*

The next step in the database development was to combine the information from the four SRTM-derived terrain thematic layers (slope, RI, PDD and hypsometry) into a single grid constituted of Terrain Units. Expectedly this grid had many small and meaningless patterns. It was therefore filtered using the FOCALMAJORITY function with a 3 cells radius circle shape neighbourhood to create a more homogeneous appearance of the Terrain Units. This grid is then vectorized to create a polygon coverage (Figure 11).

The ArcInfo® commands used for this section:
physioraw = COMBINE(slopeclass, riclass, pddclass, hypsclass)
physiofilt = FOCALMAJORITY(physioraw, CIRCLE, 3)
soterraw = GRIDPOLY(physiofilt)
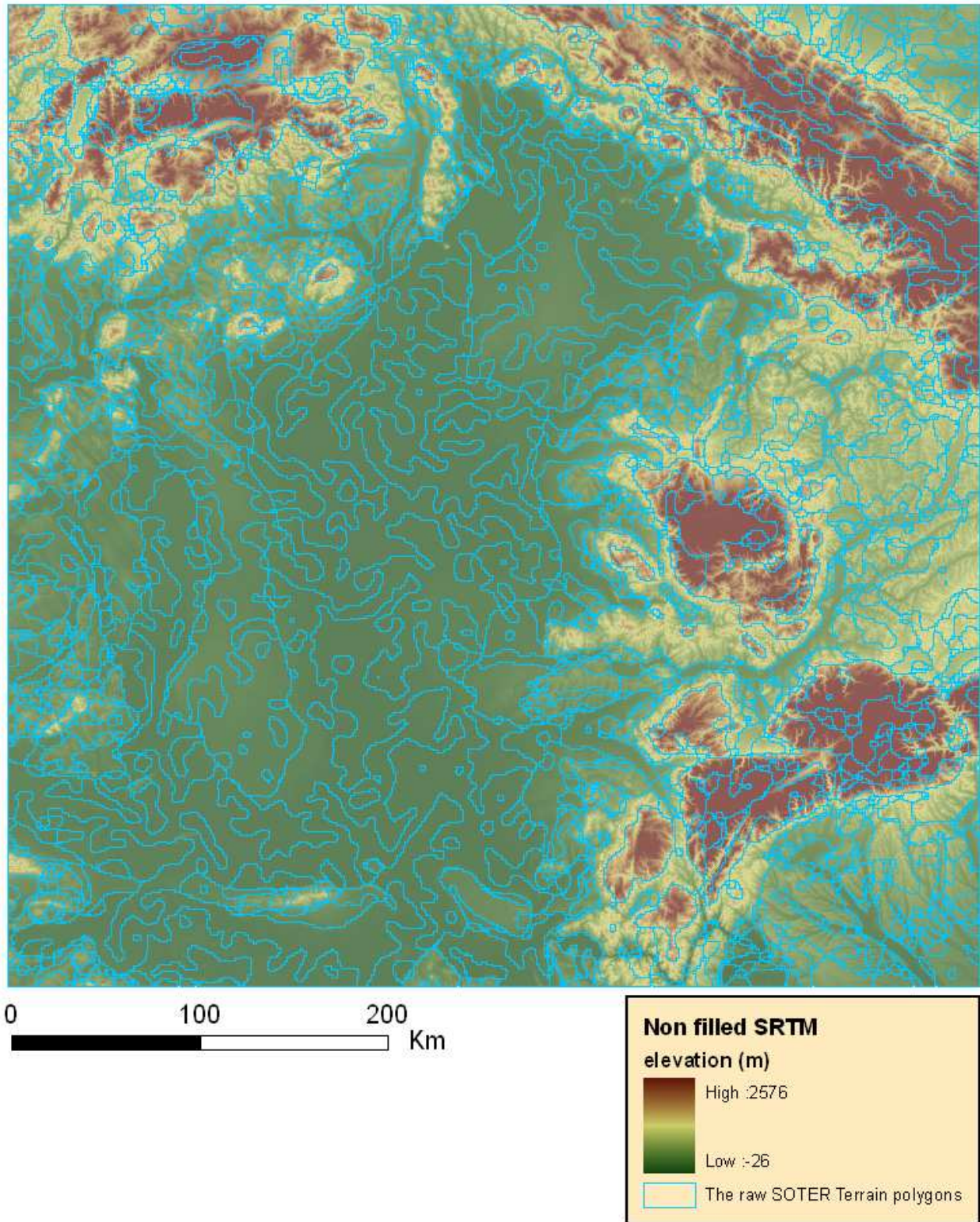
Figure 11: The raw SOTER Terrain Units structure derived from (and displayed over) the SRTM digital elevation data. The area covers the northern part of the Hungarian Great Plain and part of the northern and north-eastern Carpathians.

2.3.2.7. Vector-based generalization of the raw SOTER Terrain Units polygon system

Figure 12 shows a close view on part of the raw SOTER Terrain Units polygon system (black thick lines and red thin lines). It is evident that even after the many steps of filtering, there are still a lot of small polygons, which are below the size limit specified in the SOTER Procedure Manual (hatched polygons on Figure 12). According to the Manual, the minimum area of a polygon must be 25 km^2 if represented on a 1:1 million scale map and 625 km^2 on a 1:5 million scale map. Any polygon smaller than these thresholds, depending on the target scale, has to be aggregated with one of its neighbouring polygons, preferably with the one that has the most similar terrain characteristics. To evaluate this similarity in a quantitative manner, the Euclidean distance between each polygon pair is calculated using the same four thematic terrain layers as produced above. These distances (red numbers on Figure 12) are then used to select the neighbouring polygon that has the minimum Euclidean distance from the polygon to aggregate.
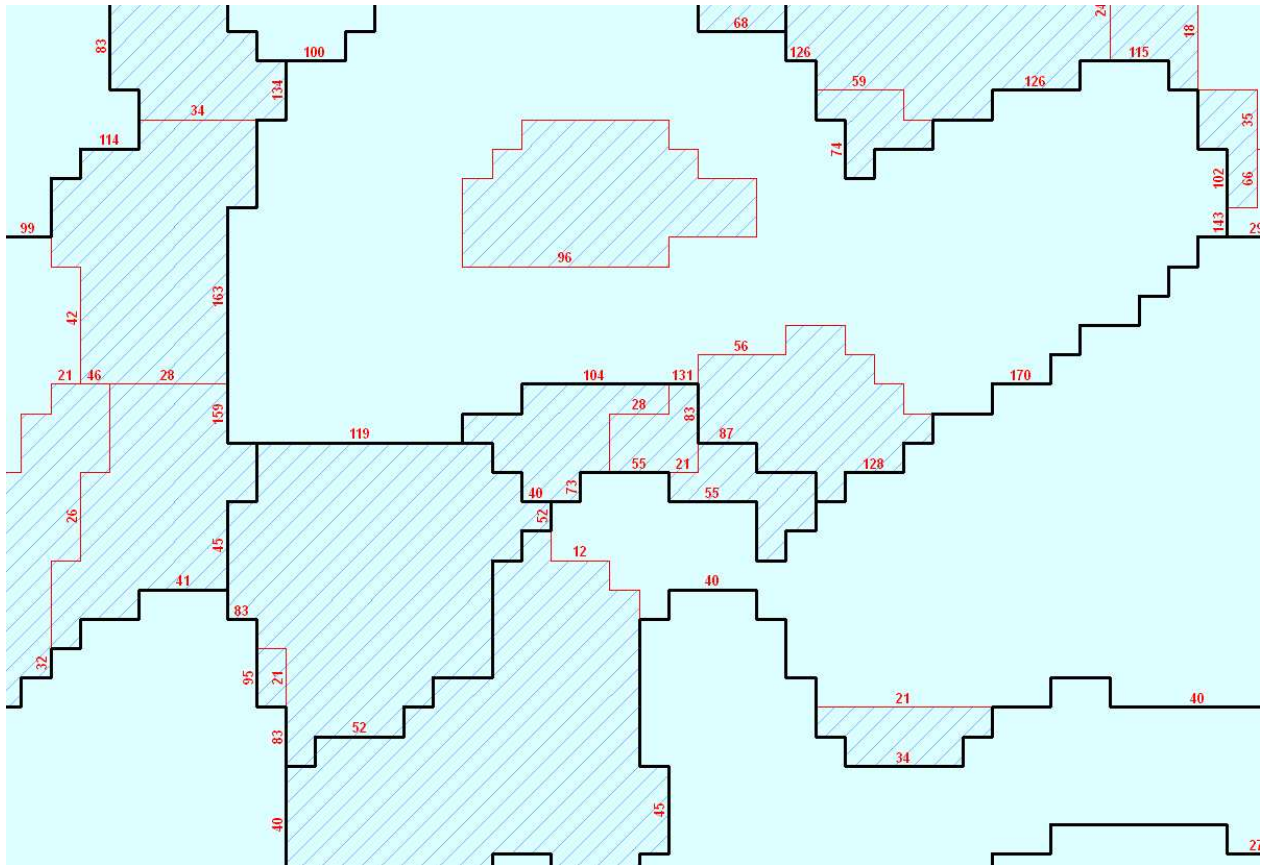
Figure 12: The minimum Euclidean distance-based aggregation procedure. The red numbers are the Euclidean distances calculated between one polygon and its neighbour. The hatched polygons are those that have a surface area below the threshold (they must be aggregated to one of their neighbours). The red thin lines are the polygon borders removed by the algorithm for aggregating.

In the first step, the four continuous landform parameter grids (slope, RI, PDD and hypsometry) are normalized to a range of 0 to 1000 using equation (1). This step is important to give equal weights to all the four landform parameters.

$$Xnorm = \frac{X - X\min}{Xrange} * 1000 \qquad (1)$$

where
Xnorm is the normalized value for parameter X in the processing cell,
X is the original value for parameter X in the processing cell,
Xmin is the minimum value of parameter X calculated from all cells in the grid layer,
and *Xrange* is the value range of parameter X (*Xmax - Xmin*) calculated from all cells in the grid layer.

At this stage, each cell is characterised by the four normalized values $SLOPE_{norm}$, RI_{norm}, PDD_{norm} and $HYPSO_{norm}$. In the second step, the mean values of these four normalized landform parameters are computed for – and assigned – to each polygon. Thus, each polygon is characterised by the four normalized mean values $SLOPE_{Poly}$, RI_{Poly}, PDD_{Poly} and $HYPSO_{Poly}$. In the third step, the Euclidean distance (*Ed*) is calculated for each neighbouring polygon pair using equation (2) and assigned to the arc that divides that pair.

$$Ed = \sqrt{D_1^2 + D_2^2 + D_3^2 + D_4^2} \qquad (2)$$

where
$D_1 = SLOPE_{PolyLeft} - SLOPE_{PolyRight}$
$D_2 = RI_{PolyLeft} - RI_{PolyRight}$
$D_3 = PDD_{PolyLeft} - PDD_{PolyRight}$
$D_4 = HYPSO_{PolyLeft} - HYPSO_{PolyRight}$
and where
$SLOPE_{PolyLeft}$ is the mean normalised slope value of the polygon standing to the left of the arc
$SLOPE_{PolyRight}$ is the mean normalised slope value of the polygon standing to the right of the arc
and so forth for each of the four parameters.

At this stage, each arc holds a quantitative estimation of the similarity between the two polygons that it separates in terms of landform characteristics (red numbers on Figure 12). In the fourth and final step, the algorithm can now select – for each of the polygons that are candidate for aggregation – the arc to delete that has the lowest Euclidean distance value of all arcs making up the polygon. Deleting that arc results in aggregating the small polygon to its most similar neighbour.
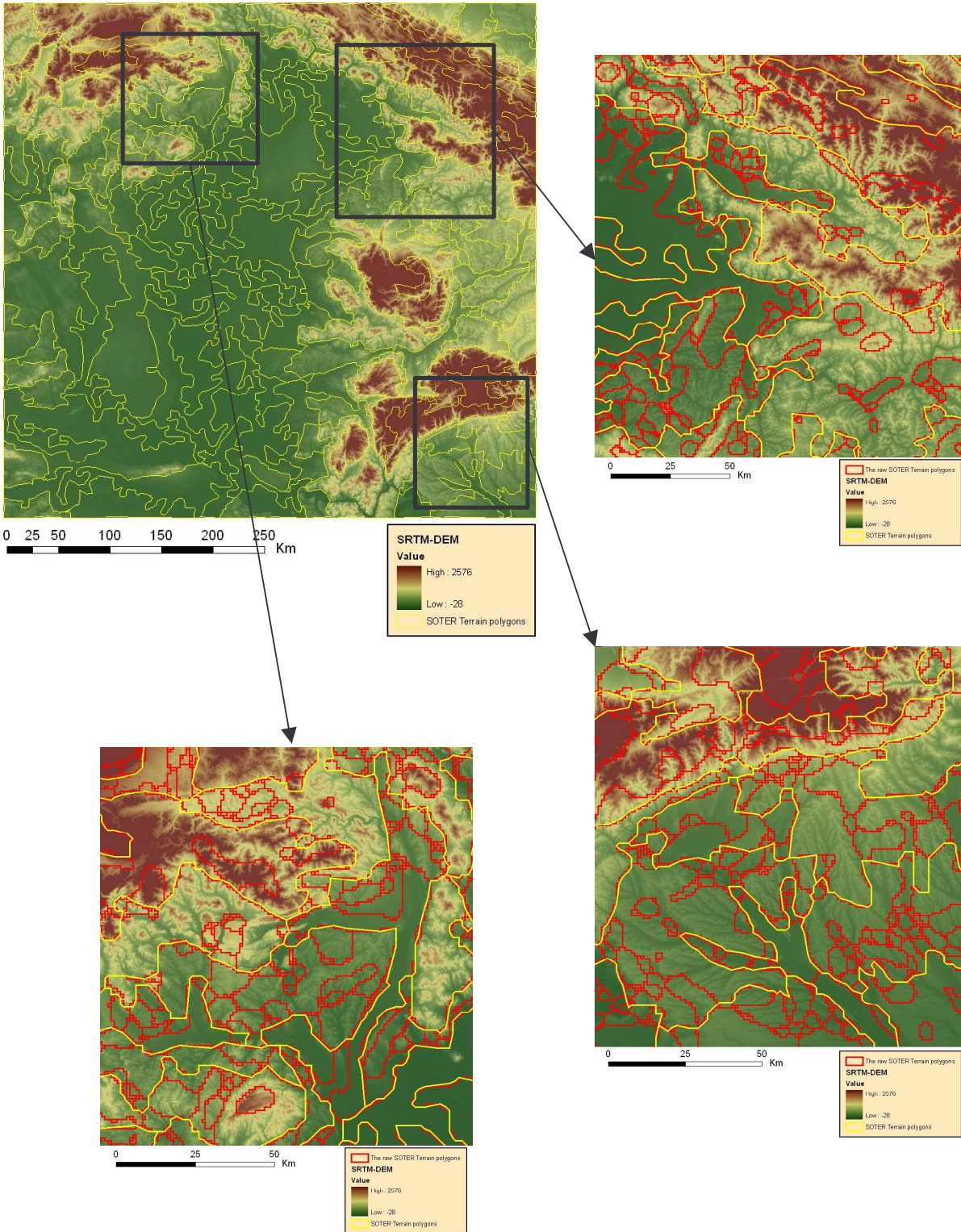
Figure 13: The results of the aggregation and line simplification procedure to the target scale of 1:5 Million in the Hungarian Great Plain and part of the Carpathians.

Aggregating several small polygons together may result in a new polygon that still has an area below the specified threshold. Therefore, the procedure is iterative. It starts again from the second step, i.e. calculating the mean values of the 4 normalized landform parameters for each newly aggregated polygon, calculating the Euclidean distances between the pairs and eliminating the arc with the smallest Euclidean distance value. The procedure is repeated until the resulting polygon system remains stable.

The procedure was implemented as a standalone AML tool, which can either be downloaded from the JRC's Soil and Waste Unit homepage or provided by the authors on request.

2.3.2.8. *Line smoothing and simplification*

In a vector GIS data form, polygons are structured into a set of arcs, which in turn are structured as a set of vertices (X and Y coordinate pairs). It is meaningless to keep vertices that are closer to each other than the specified resolution of a geographic database. Resolution is related to nominal scale, i.e. the scale at which the database is meant to be used. As mentioned above, the SOTER Europe project targets both the 1:1 and 1:5 million scales. At these target scales, it is commonly admitted that the resolution can be set to 200 and 1000 m respectively. This is because these values match with 0.2 mm on map printouts of the corresponding scales, 0.2 mm being the commonly admitted separability distance between features on a map.

Therefore, the arcs that make up the SOTER Terrain Units polygon system output from the aggregation procedure were generalized. Using the GENERALIZE command in ArcInfo® with the specified tolerance, lines are simplified to comply with the targeted resolution.

Figure 13 shows, on three highlighted areas, the results of applying the small polygon aggregation and line generalization procedure displayed at the target scale of 1:5 million.

Line simplification alters polygon topology and sometimes results in dividing polygons into smaller ones. These can then become smaller than the specified threshold area. The overall procedure – both aggregation and line simplification – therefore needs to reiterate. There again iterations repeat until the resulting coverage reaches a completely stable state.

The overall procedure was implemented as a standalone AML tool which can either be downloaded from the JRC's Soil and Waste Unit homepage or provided by the authors on request.

3. Results and Discussion

Figure 14 shows the four terrain variables derived from the SRTM DEM grid for the eastern half of the Carpathian basin. The resulting data sets were found to be realistically characterizing the terrain. Although, the centre and south-western part is a low relief area (Hungarian Great Plain) with little terrain variability – expressed as only a few meters range in elevation –, this variability is still the most important factor controlling the soil formation processes. In contrast, it is evident from all four derived terrain variable images that the ring of the Carpathians surrounding the plain shows strong variations in the terrain. The challenge of this study was to capture all the significant natural physiographic variation on both plain and hilly

27

areas by applying a quantitative, consistent procedure and using the 3 arc second resolution SRTM DEM.

Figure 14: Maps of the four classified landform parameters in the pilot area. Please refer to the method section for the class meanings.
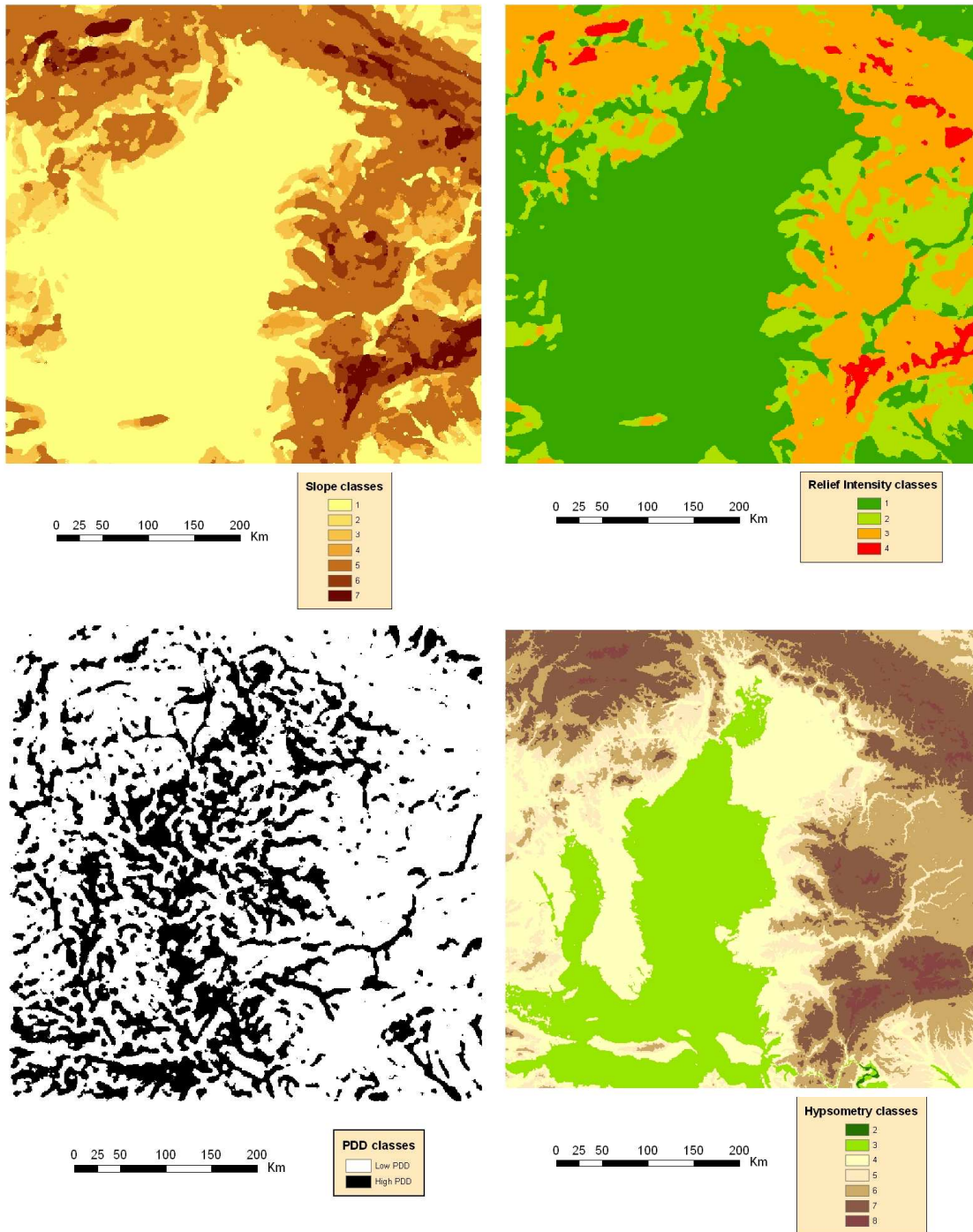
Dobos *et al.* (2004) were using a coarser resolution 30 arc seconds SRTM DEM (~1 km) for delineating SOTER Terrain Units. They concluded that the spatial detail needed for deriving a 1 to 1 million scale database is well achieved with such a 1 by 1 km resolution dataset. However, a coarse spatial resolution DEM tends to "over generalize" the terrain features by decreasing their value ranges. They highlighted this problem and called for research to solve this limitation.

The approach developed here is an attempt to take advantage of the availability of a fine spatial resolution DEM. The thematic terrain variable layers were derived from the 90 m resolution DEM to keep as much details of the landscape information as possible. These resulting images were classified based on the SOTER criteria. The necessary spatial generalisation of the terrain parameters to the level of detail requested by the targeted scale of the SOTER project were done only at the next stages of the procedure. In the first stage of the generalisation procedure, the parameter grids were resampled to coarser resolution. This could have been done by averaging the fine resolution (non-classified) cell values to the coarser resolution one and then classify this spatially degraded grid. But doing so would have taken us back to producing unrealistic classes, which may not even exist on the area. Instead, a "blocking" approach was chosen to achieve this step of the generalisation procedure. Blocking consists in assigning the most frequently occurring class value within a block of cells to the entire block. Doing so has several advantages over averaging: i) it maintains the "most important" information within a block, ii) it maintains the variability inherent to the entire dataset, and iii) it is a "sensible" and "authorized" operation on class values. The first step of the generalisation procedure for the 90 by 90 m cell images thus consisted in majority blocking to 11 by 11 cells blocks (990 by 990 m) followed by simply resampling the blocked images to 990 by 990 m cell size images. The method is illustrated on Figure 7 and Figure 8 and was applied to the four landform parameter images. As made evident from the figure (Figure 7: Classified slope and Resampled, classified slope), the method keeps the original classes within the area, showing no trend to shift them downward. Further filtering the image (Figure 7: Majority filter with 4 cells radius) however shows a tendency to enlarge solid, homogeneous patterns and extend their area over the neighbouring, more heterogeneous areas. This is why filtering must use a relatively small moving window size to minimize this effect.

Both the BLOCKMAJORITY and the FOCALMAJORITY functions have a negative side effect. When more than one majority class occurs within a block or focal neighbourhood (two or more classes are found in the same number of cells within the processing window), the function cannot decide among them and assigns "*no data*" to either all cells within that block (BLOCKMAJORITY case) or to the centre cell of the focal processing window (FOCALMAJORITY case) (see the white spots in Figure 7). Introducing a second filtering step with a larger window is a turnaround "trick" to get rid of almost all these "*no data*" cells by simply picking up for them a value that is found within a larger neighbourhood. The insignificant portion of "*no data*" cells that still remain even after applying this method is treated in the later stages of the generalisation procedure, namely with using the polygon aggregation algorithm. It is a more "intelligent" and target oriented procedure and uses the cell properties directly, instead of estimating the cell class based on its neighborhood characteristics. However, running the algorithm on a database having a lot of tiny neighbouring polygons with often missing bigger, dominant adjacent polygons to join, the product of the aggregation would be influenced much more by order of polygon processing than by the semantic characteristics of the polygon and would result in a random like aggregation of these polygons. That is why filtering was necessary first to decrease the number of polygons to an acceptable level. The polygon aggregation function

29

was then used to deal with the rest of the "*no data*" polygons. Thus, a raster based filtering and a vector based aggregation was found to be the optimal combination for generalization.

As it was suggested by the SPM workshop, new classification schemes were introduced for the four landform parameters derived from DEM data. This paper does not aim to discuss their benefits and impacts. The only conclusion made from the visual interpretation of the polygon system – built using these classified landform parameters – is that the new scheme follows well the geomorphologic units of the landscape and creates meaningful delineation. The changes in the class limits for slope and hypsometry were found to be a great improvement. The new slope classes make a smoother and better discrimination of the land. The classes are grouped around the most frequently occurring values, therefore making a more balanced distribution among them. This phenomenon is even more evident with the hypsometry classes. New classes were introduced to improve differentiation among the landscape units on the low-lying plain areas, where the elevation above the sea level is almost the only significant terrain factor besides the PDD.

Three of the four terrain variables, namely the slope, RI and hypsometry, have not any contribution to the plain area characterization (Figure 14). The hypsometry classes contribute a little, but just "accidentally" here because the Hungarian Great Plain lies along the 100 m altitude class limit. The only parameter, which contributes to the landscape unit delineation on a plain area, is the PDD. The slope and RI parameters, complemented with the hypsometry, are very efficient in characterizing the landscape of the hilly and mountainous lands. The combination of these three elements creates a very detailed physiographic characterization even without considering the PDD parameter. A large portion of the information provided by the PDD for these higher relief regions is already delivered by the other three parameters. However it is evident that the PDD carries much additional information over the other three parameters, but this appears mainly on a higher scale, not appropriate to the target scales of this project. As opposed to the high relief areas, only the PDD can provide meaningful information for unit delineation within the plain areas by highlighting the depressions and low lying areas where wetness potentially occurs. Using the three dissection classes suggested in the manual would result in a lot of details and small patterns not adequate at the target scales. Instead, only two classes were created and adjusted to delineate both the low lying areas and valley bottoms in hilly and mountainous regions, and the depressions in plain areas. The class boundaries were defined empirically by testing different setups and matching them to real physiographic features.

The pilot area selected for the study was quite challenging due to its very complex natural and anthropogenic geomorphologic patterns. Starting from the second half of the nineteenth century an extensive dike system was built along the major rivers of the Hungarian Great Plain to prevent a huge area from annual floods and to expand agricultural land. At that time, it was often difficult to identify the major watercourse because huge areas were completely covered by ponding or flooding water appearing as temporal lakes. Nowadays the geomorphologic setup of the Plain still resembles to the one from before the dike system. Huge low lying areas, depressions, narrow sand barriers, sand dunes, loess plateaus and old, abandoned river beds create a mosaic of geomorphologic patterns (Figure 15). This picture was further diversified by the man made dike and channel structure. Dikes along the Tisza River are captured in the SRTM DEM data and are visible on the DEM image as well (see the brown linear pattern along the Tisza River, pointed with two arrows on Figure 15). This of course has a significant impact on the drainage network determination necessary for deriving the PDD. The PDD is generally

successful at detecting depressions and local heights. However, the area along the Tisza River is quite problematic. Dikes, especially where the surrounding area is relatively high as well are often taken as heights, preventing the water from flowing through to the river and are thus classified as local elevated areas. This phenomenon extends the area of the natural heights over the low laying ones (see the polygon peninsula extending along the Tisza and pointed by the two arrows). In other cases, where the low lying character of the surrounding area is strongly expressed, thus collecting a lot of drainage lines, these lines are trapped along the dikes on both sides of the river. This creates a high drainage density for those areas, despite of the existence of the dikes (see the lower left corner of Figure 15). In contrast to the above case, these are classified as a low lying areas. Although this effect hampers the continuous delineation of the Tisza River channel and shifts the balance towards the low PDD area over the high one, it is not as erroneous decision as it may appear. Indeed, dikes have a great impact on the surface water flow, which impact is reflected on the image as well.

The RI classification has changed a lot after the SPM workshop, but mainly in a formal way. The various RI units that were used in different contexts within the previous methodology were replaced with one common unit: *m/[area of a 1 km diameter circle]*. This new unit still maintains a link to the original SOTER RI units while it is easier to handle within a GIS and meets the definition used by geographers for that measure.

The final step in the procedure aims at generalizing the polygon system so that it meets the requirements of the SOTER Manual regarding the target scales: polygons that are below the minimum size limits of 25 and 625 km^2 at the 1:1 and 1:5 million scales respectively must be eliminated and polygon borders must be simplified. Figure 16 and Figure 17 show the resulting images for the pilot area at these two target scales. Figure 18 is a zoom into the lower right corner of the pilot area. It shows all three polygon systems together to give an idea of the effect of the procedure: the raw polygon system as derived directly from the grids (blue lines), the polygon systems produced for the 1:1 million (red lines) and 1:5 million (yellow lines) target scales are displayed.

The procedure eliminates small polygons by aggregating each of them with its most similar neighbour. Similarity between a small polygon and its neighbours is measured by considering the Euclidean distance between their respective landform characteristics. The most similar neighbour, namely the one that is at the smallest Euclidean distance, is selected for aggregation.

On our dataset, despite reducing the number of polygons by 82 % at the 1:1 million scale (see the Technical notes at the end of the paper), aggregation still moderately altered the original polygon system. Only small, few cell-sized polygons were eliminated, while the overall look of the polygon system was well kept. At that scale, most of the landscape units that are visible on the SRTM image have been successfully delineated. With hardly any exception, all the blue polygons on Figure 18 that were aggregated to form the red ones were correctly assigned.
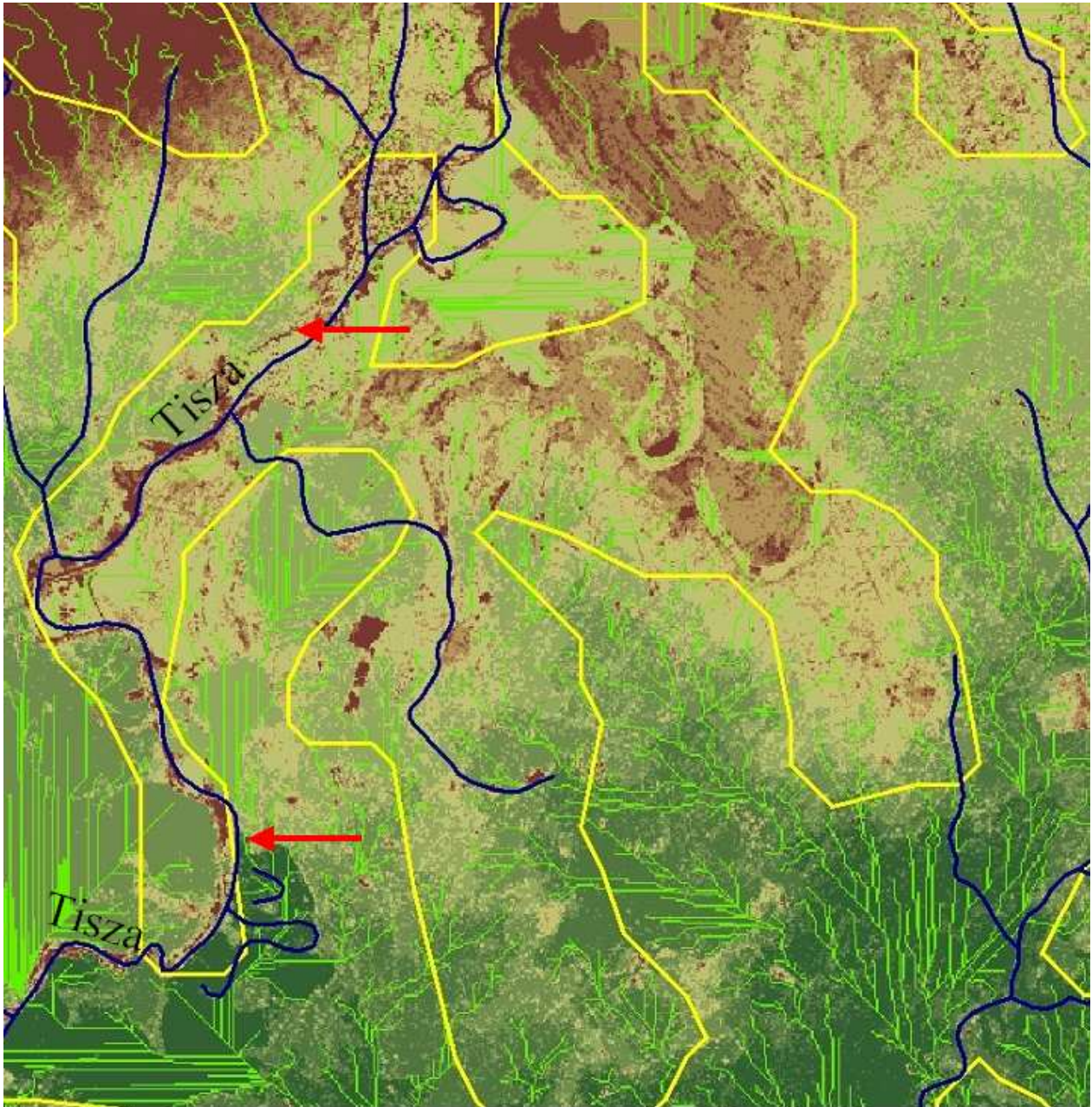
Figure 15: A 50 by 50 km zoom into the Tisza Valley on the Hungarian Great Plain. The 15 m elevation range (81 to 96 m above sea level) is represented with green to brown colours. Yellow lines show the resulting 1:5 million SOTER polygon system borders. Blue lines show the actual drainage system (rivers, streams and channels) whereas the green ones show the drainage system derived from the SRTM DEM as part of the PDD procedure. The red arrows highlight some of the dikes along the Tisza River.
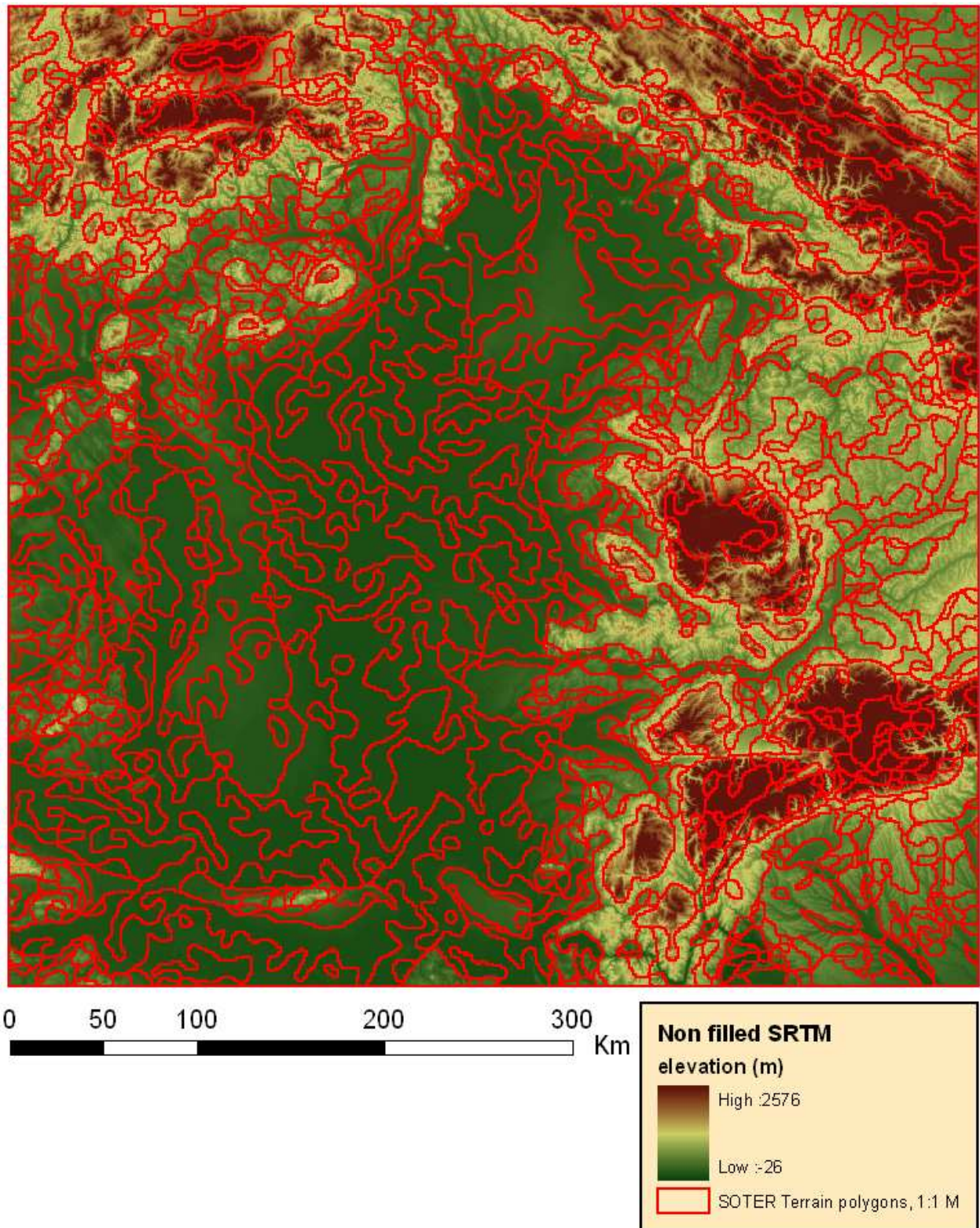
Figure 16: The generalized polygon system derived from SRTM DEM data to produce the 1:1million scale SOTER Terrain Units for the Hungarian Great Plain and for part of the Carpathians.
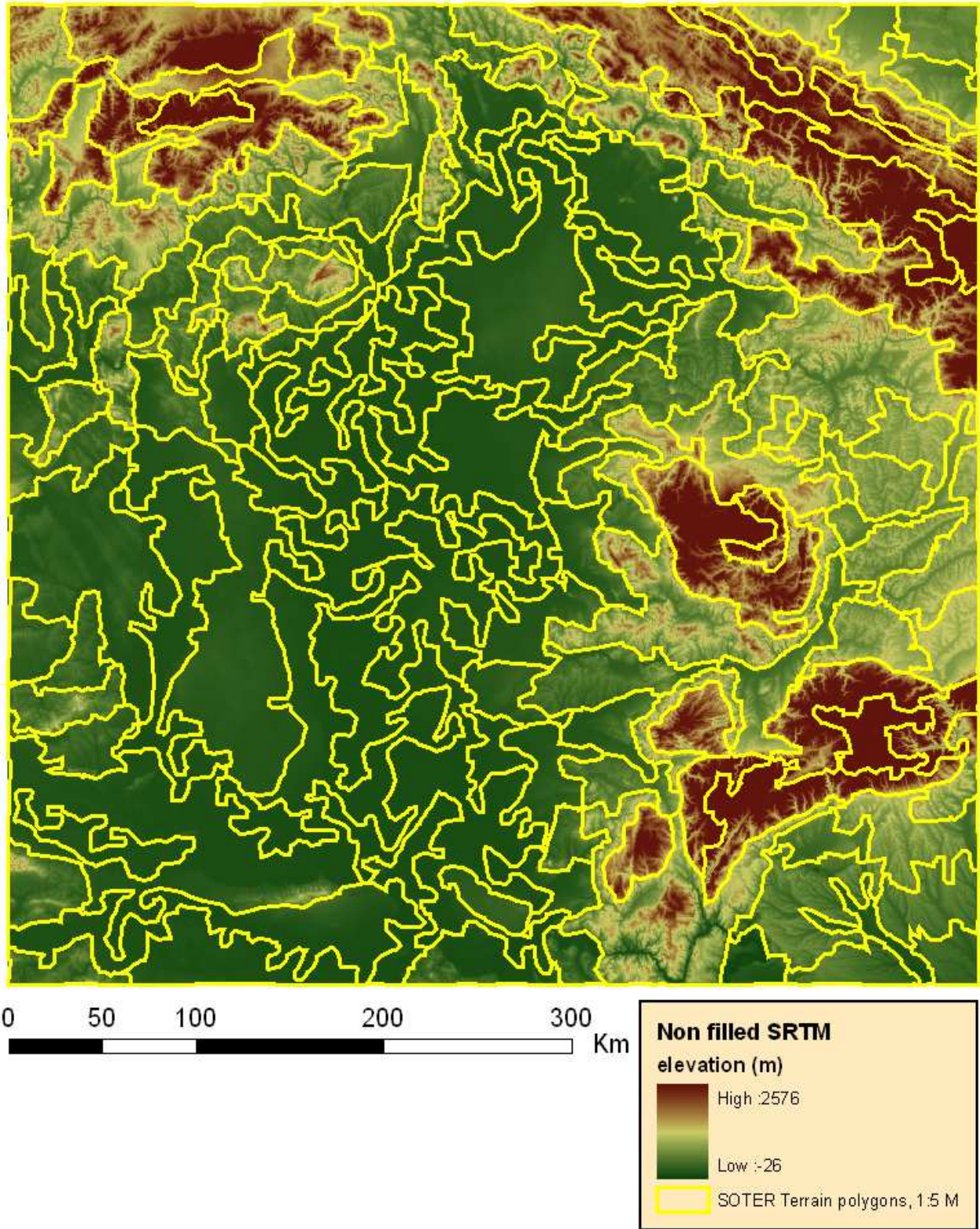
Figure 17: The generalized polygon system derived from SRTM DEM data to produce the 1:5million scale SOTER Terrain Units for the Hungarian Great Plain and for part of the Carpathians.
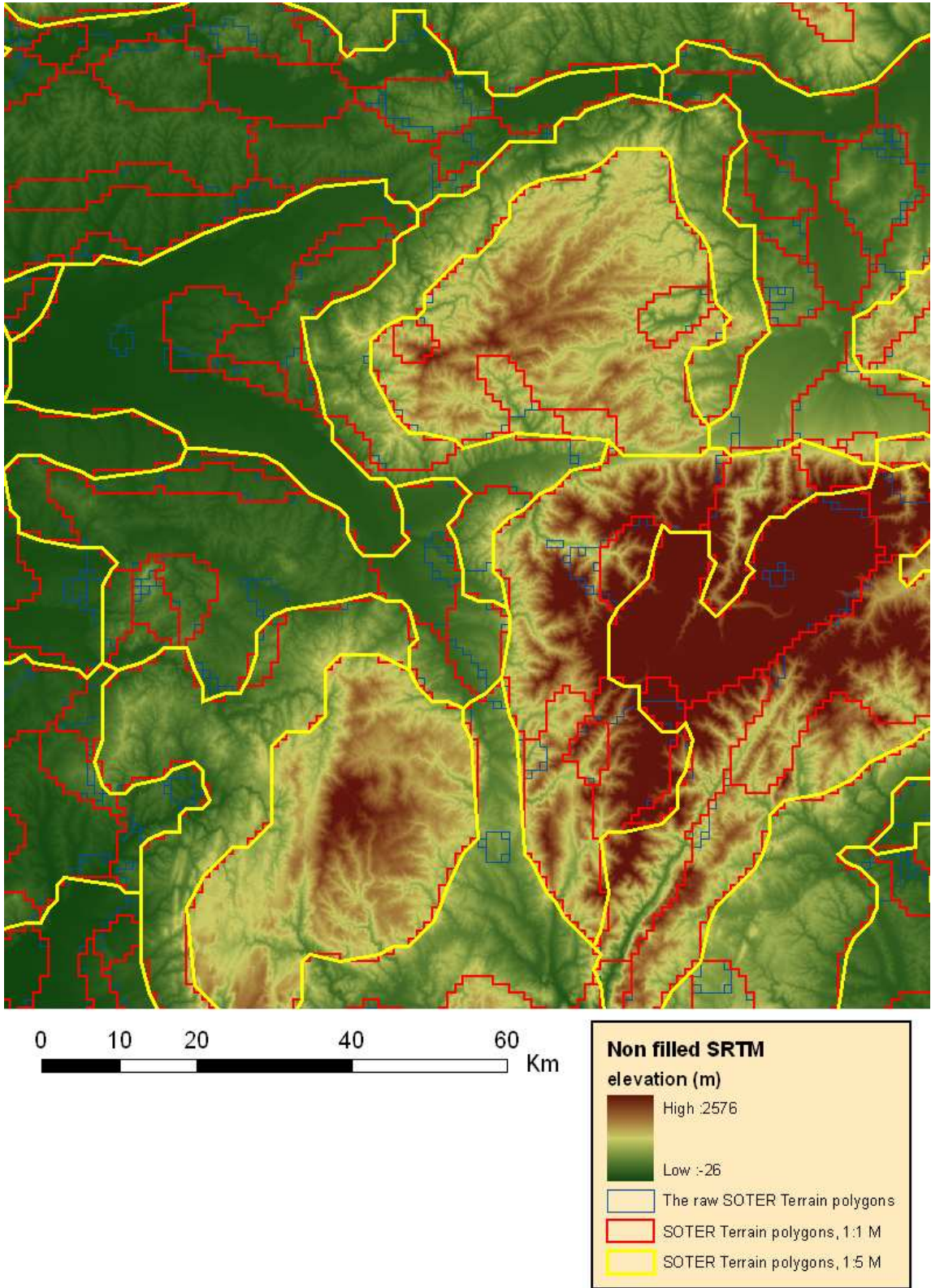
Figure 18: The SOTER Terrain Unit structure aggregated to 1:1 and 1:5 million scales.

As expected, aggregation to the 1:5 million scale resulted in a more drastic change of the polygon system, reducing the number of polygons by 98 %. Characteristic – sometimes very different – landscape units had to be combined in a meaningful way. This required a lot of compromise, especially when a small intrusion had to be eliminated but none of its neighbours was really similar. Nevertheless, the algorithm generally performed successfully and no major problem was identified on the resulting polygon system. Many of the linear features such as valleys bottoms were kept in the output and meaningful Terrain Units were formed, appropriate for the target scale.

Generalizing polygons means also generalizing the borders of the polygons that remain after aggregation so that their resolution meets the target scale. The corresponding tolerances (200 and 1000 m) were chosen according to cartographic common sense (0.2 mm on a map at both scales). Generalizing the arcs is achieved through line simplification. Among the two algorithms provided within the ArcInfo® GENERALIZE command, in our case and only by visually inspecting the results, the Douglas-Peucker algorithm (1973) (called through the POINTREMOVE option) appeared to behave better than the shape recognition one (ESRI, 1996) (accessed with the BENDSIMPLIFY option). A "cosmetic" side effect of the line simplification is that the stair-like appearance of the arcs due to the vectorization of the original 990 by 990 m grid cells is smoothed out. Applying both polygon aggregation and line simplification reduced the number of vertices (coordinate pairs) in our dataset by 53 and 89 % at the 1:1 and 1:5 million scales respectively, thus drastically reducing the database volume. Regardless of the scales the aggregation method produces more or less homogenous Terrain Units giving very satisfying results.

4. Conclusions

The development of a quantitative procedure is seen as a promising way to speed up the completion process of the global SOil and TERrain project. Many segments of the digital soil mapping technology have been made available since the late 1990s. Numerous studies were carried out to test the usefulness of digital elevation data for soil survey and characterization and much knowledge has been accumulated on this topic. The Shuttle Radar Topography Mission (SRTM) project developed a global digital elevation model (DEM) coverage, which is now freely available and easily accessible for use. This emerging set of data and technology can help creating a common platform for the SOTER database development. It was agreed at the last SOTER Procedure Modification (SPM) workshop, that a Manual of Procedure for SOTER Terrain Unit delineation based on a DEM had to be developed and attached to the upcoming version of the SOTER Manual.

The authors took this opportunity to develop a procedure and test it in the context of the SOTER project for the European Union. This pilot study aimed at making a step forward on this road by creating a methodology for incorporating DEM into the SOTER procedure.

This paper describes this new, quantitative method for creating a SOTER Terrain Unit polygon system. The method is designed for mapping large areas of the world quickly and cost effectively. The resulting SOTER database will have the advantages of quantitatively derived databases, namely consistency, homogeneity, limited data generalization problems, and will avoid edge-matching and harmonisation problems. The procedure is based on the SOTER Manual specifications and is meant to be compatible with the datasets formally developed using

the traditional way. But it also incorporates the procedural changes, which have occurred since 1995, when the last revision of the Manual was published.

The procedure has been tested on a representative pilot area covering the eastern half of the Carpathian Basin. The results are satisfying. The delineation of the terrain features is appropriate to the targeted scales. Meaningful and homogeneous geomorphologic units were identified at the 1:1 million scale. More complex but still uniform units were identified at the 1:5 million scale as well.

The method is used to develop the SOTER database for the states of the European Union. Further refinement and characterisation of the Terrain Units will be done using the Soil Geographical Database of Eurasia at scale 1:1,000,000 (King *et al*., 2002).

5. Acknowledgement

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7. Technical notes

Generalization results for the 1:1 million:

```
Arc: &run generalize_polys soterraw tu soter1m mlf.dis similarity_distances
1000000 .2 25

  After 3 iterations one moves
    from coverage SOTERRAW to coverage SOTER1M
    from 6589 to 1167 polygons (-82%)
    from 18151 to 3370 arcs (-81%)
    from 69495 to 32684 segments (-53%)

  Proportion of the area in resulting SOTER1M polygons effectively
  concerned by the predominant value of TU (key item):
    minimum:     23.636363983154297%
    mean:        86.632505730944672%
    maximum:     100.00000000000000%
    std:         17.280993168451701%

  Program generalize_polys.aml
      started on 31 Jan 05 15:33:36 Monday
      ended on   31 Jan 05 16:06:53 Monday
  Elapsed time: 0.55444444444
```

Generalization results for the 1:5 million:

```
Arc: &run generalize_polys soterraw tu soter5m mlf.dis similarity_distances
5000000 .2 25

  After 3 iterations one moves
    from coverage SOTERRAW to coverage SOTER5M
    from 6589 to 120 polygons (-98%)
    from 18151 to 350 arcs (-98%)
    from 69495 to 7383 segments (-89%)

  Proportion of the area in resulting SOTER5M polygons effectively
  concerned by the predominant value of TU (key item):
    minimum:     13.505257606506348%
    mean:        55.283419232408541%
    maximum:     98.905235290527344%
    std:         26.534571550618274%

  Program generalize_polys.aml
      started on 28 Jan 05 17:01:47 Friday
      ended on   28 Jan 05 17:42:37 Friday
  Elapsed time: 0.68055555556
```

39

Potential Drainage Density Index (PDD)

Endre Dobos & Joël Daroussin

Joint Research Center, Institute of Environment and Sustainability, Soils and Waste Unit, TP 280, 21020 Ispra (VA), Italy

This paper focuses only on the technical details of the usage and creation of PDD. More details on the theory can be found in the papers written by Dobos (1998) and Dobos *et al.* (2000).

The Potential Drainage Density index, abbreviated as PDD, can be used for geomorphologic, pedologic and geologic characterisation of the landscape.

PDD is a measure of landscape dissection. The degree of surface dissection is determined by the surface runoff and the permeability of the soils and of the underlying rock strata. The less the water infiltrates into the soil, the higher is the water runoff on the surface, causing erosion and dissecting the land surface. Thus, the surface runoff is inversely proportional to permeability. A sandy parent material absorbs the majority of the surface water income, so there is basically no, or only limited runoff. A clayey parent material produces the most dissected surface, due to the very limited permeability and high surface runoff and erosion. Therefore, the landscape dissection is an indirect indicator of the soils and bedrocks.

Dissection is difficult to measure. A potential approach to characterize the degree of landscape dissection is to measure the total lengths of valleys or drainage lines. Drainage density (D) is the total length of the permanent and seasonal streams and rivers divided by a unit size of area (A):

$$D = \frac{\sum_{1}^{n} L}{A}$$

where "L" is the length and "n" is the number of rivers. Unfortunately, real drainage density is also difficult to measure, because it requires good topographic maps in an appropriate scale. Instead, the quantitative approach of PDD is presented here. PDD is a terrain attribute, which can be derived from Digital Elevation Models (DEM). The word "Potential" was added to the name 'Drainage Density' to emphasize the difference between the actual drainage density as could be measured in the field and the DEM-derived one.

40

Any software equipped with hydrological modelling tools can be used to derive the PDD index.

In practice, PDD is used to delineate ridges, backslopes and valley bottoms on high relief areas, i.e. hilly and mountainous regions (Figure 19). Low PDD values represent local heights, elevated areas, ridge tops. Intermediate values represent backslopes, with higher values for the steeper sloping and lower for the more gently sloping areas. High PDD values refer to low-laying areas, depressions, valley bottoms and basins (Figure 20). On flat areas, where the relief is very low, PDD highlights depressions and local lows, where the surface drainage system forms a convergent flow channel pattern. Such a pattern often results in extremely high PDD values.
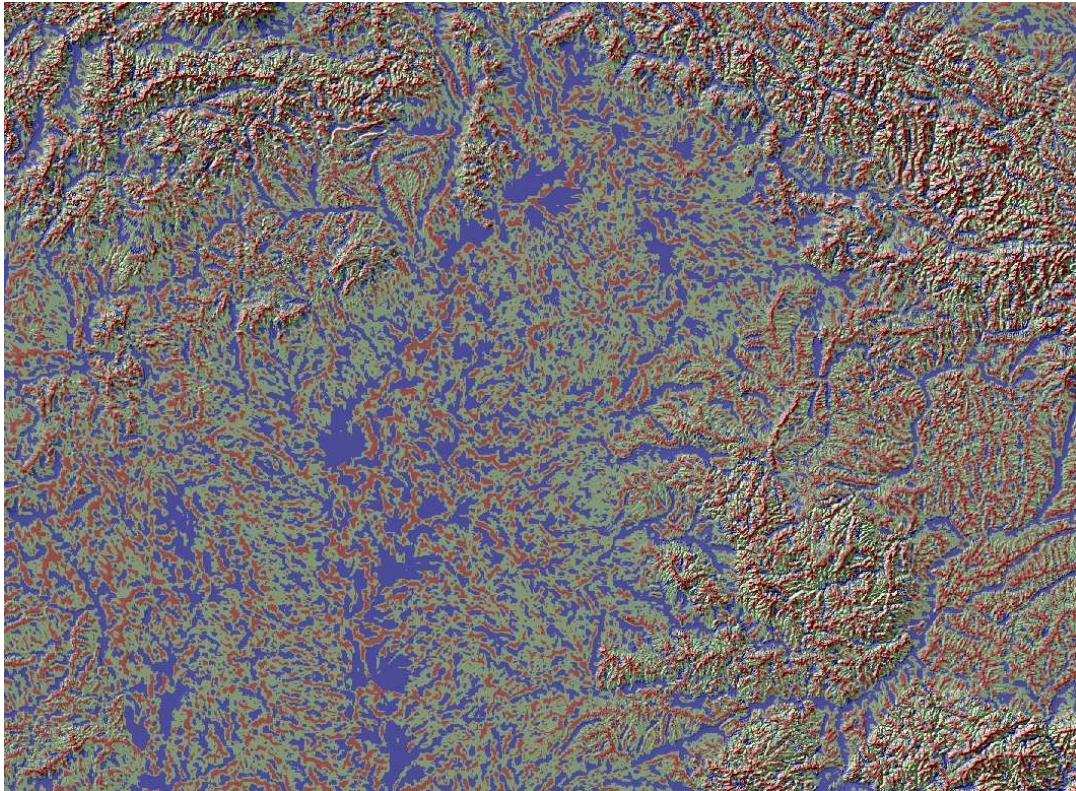
Figure 19: A classified PDD image of the north-eastern part of the Carpathian-basin covering the major part of the Great Hungarian Plain and sections of the Carpathians. Brown colour represents ridges and local heights, greenish colour stands for backslopes and transitional areas, and blue for depressions and valley bottoms.

41
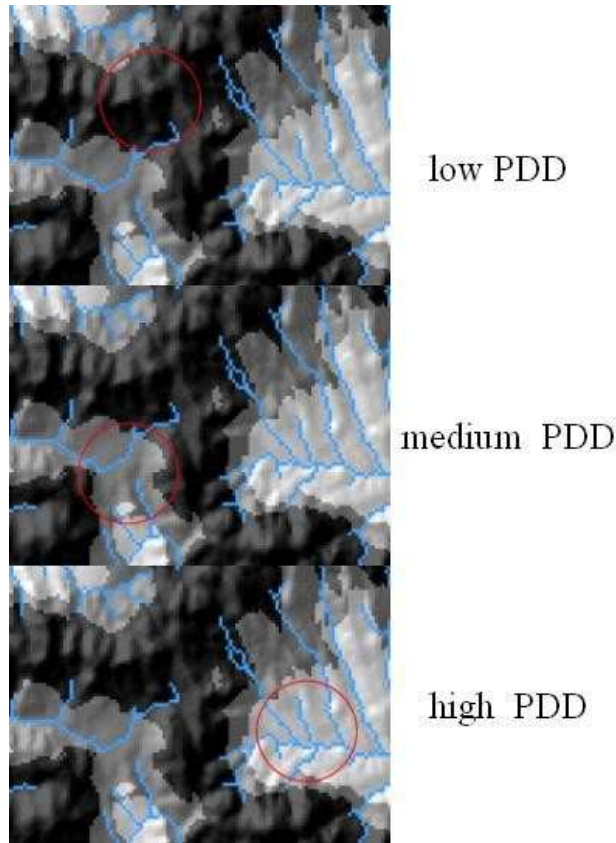
Figure 20: Low, medium and high drainage densities within a circle-shape neighbourhood window.

8. The derivation of the PDD Layer

Most raster based Geographic Information System (GIS) software packages have built-in tools that can be used for this purpose. In this example, ArcInfo GRID commands and functions are used to describe the procedure. For their detailed descriptions, please refer to ArcInfo manuals.

8.1. Input DEM

Running the PDD procedure requires a depressionless or hydrologically corrected DEM. Sinks due to errors in the data have to be removed from the DEM. This can be done using the FILL command of the ArcInfo® GRID module. However, it is often difficult to distinguish the sinks, which naturally occur in the data (e.g. sinkholes in karst regions) from those that are erroneous. Filling all sinks regardless of this characteristic may remove all natural depressions. In our data this has the effect of leveling up to the same elevation huge natural plain areas. By doing so, we loose all chances of differentiation on the plain areas, where few meters or even centimetres of elevation range represent a great variety of natural conditions. Instead of filling all sinks, it is therefore more appropriate to introduce a sink depth limit. Any sink deeper than the specified limit will be kept untouched. Only the sinks less deep than the threshold will be filled up to the level of their pour point. Our experience with the 90 m resolution Shuttle Radar

Topographic Mission (SRTM) DEM data showed that a threshold value of 20 metre helps to remove the majority of the small sinks, while keeping the major elevation patterns untouched on the Pannonian plain. Of course this is in view of our objective to obtain a picture of the dissection of the area but not necessarily to obtain a hydrologically correct DEM.

8.2. Flow direction

Within the ArcInfo® GRID environment, the FLOWDIRECTION function can be used to create a grid/image of flow direction. The flow direction is the direction from each cell to its steepest downslope neighbour. The flow direction (Jenson and Domingue, 1988) is based on the highest drop value calculated for each of the eight neighbouring pixels as:

$$\text{drop} = \frac{(\text{change\_in\_elevation\_value})}{(\text{cell\_center\_distance}) * 100}$$

If the descent to all adjacent cells is the same, the neighbourhood is enlarged until the steepest descent is found.

8.3. Flow accumulation / Contributing area / Catchment area

Based on the flow direction grid, the size of the contributing area to each grid cell can be calculated with the FLOWACCUMULATION function. The output grid represents the catchment area size of each grid cell expressed as cell counts.

8.4. Drainage network

Applying a threshold value to the flow accumulation grid can create a stream network. All cells, which have a contributing area higher than a certain threshold value, are assigned a value of 1, representing the drainage path. All other cells, which have a flow accumulation value below the threshold are assigned "*no data*" and become background cells (Figure 21).

The threshold value is set by the user. There is no certain quantitative rule to define it. For a 100-meter resolution DEM a threshold value of 100 cells (1 km^2 area) has been found to provide a realistic density of drainage lines characterizing well the real landscape. As the resolution becomes coarser, the representation of topography gets less detailed, while the area represented by one pixel is increased. Keeping the original minimum size of the catchment area would increase the drainage density unrealistically, thus the minimum catchment has to be increased as well. We found that taking the 100-meters pixel size as a basic case, the incremental rate in pixel size can be used as a multiplication factor for the catchment area size. For example, as we move from 100 to 500-meters pixel size, the size of the catchment area should be increased from 1 to 5 square kilometres, while the number of threshold pixels is decreased from 100 to 20 accordingly.

43
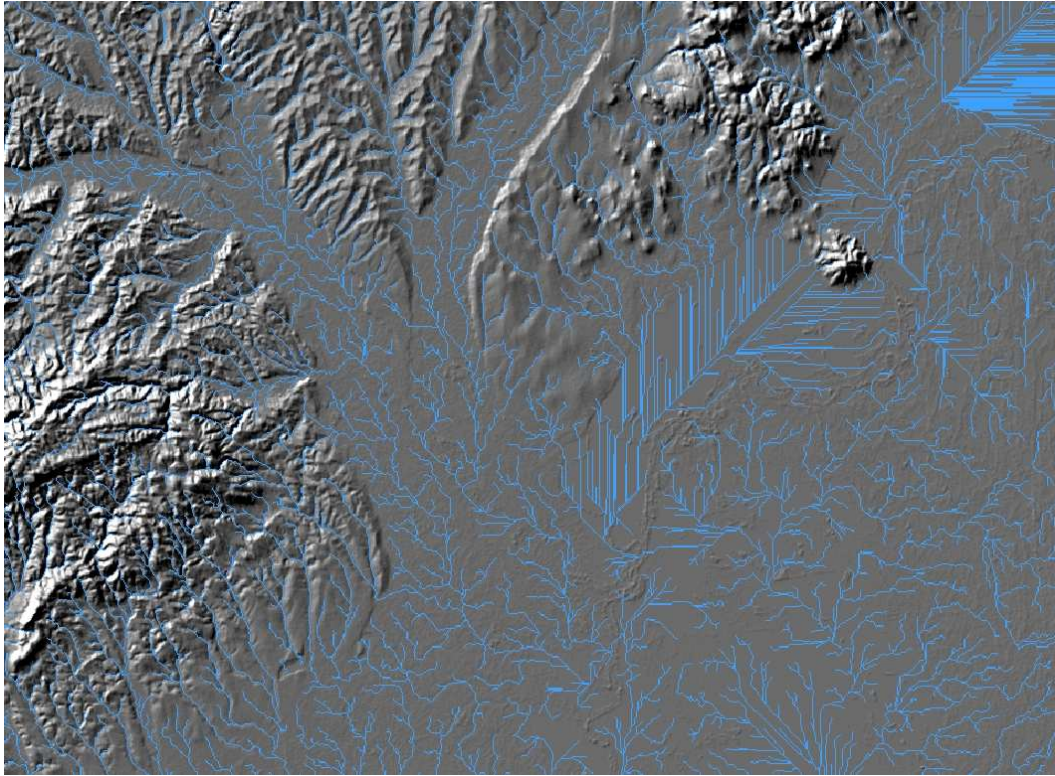
Figure 21: The drainage network derived from the 90 m resolution SRTM

From Figure 21 the reader can identify some artefacts in the form of parallel, densely located drainage lines. This pattern occurs on areas where the original image had sinks that were filled up and levelled to large flat areas by the FILL command of ArcInfo® GRID to make the drainage network creation possible. On such flat areas, the program has difficulties with identifying the flow direction, because the descent to all adjacent cells is the same. In this case the neighbourhood is enlarged until the steepest descent is found. This procedure results in straight parallel lines running towards the pour points, which often produces a very high drainage density. Although it is an artefact, the interpretation is still valid and useful because this pattern highlights depressions within the landscape, which are generally representative of valley bottoms.

8.5. Potential Drainage Density (PDD)

The final step of creating the PDD image is to run the FOCALSUM function on the drainage network layer. The function sums up the cell values that fall within a predefined shaped and sized neighbourhood and assigns the sum to the centre cell. In our case, summing is equivalent to a simple count of the cells representing drainage lines as they all have a value of 1. The neighbourhood window then moves through the entire image and calculates the PDD value for every pixel.

For computing the PDD, a circle shape neighbourhood is chosen for which a radius expressed as a number of cells has to be specified. The radius size can vary based on the need of the user. However, in order to produce a full, continuous coverage of the area, one should make sure that the size of the radius is big enough for the function to always 'catch' at least one drainage cell so as to avoid having empty neighbourhoods. A large radius tends to generalize the image, while a smaller one helps to maintain the physiographic patterns. Moreover, enlarging the neighbourhood increases computing time, which is a problem when a large DEM is used. As an example the image of Figure 22 was produced from a 90 m SRTM DEM, with a drainage threshold of 100 cells and a FOCALSUM radius of 15 cells. Figure 23 presents the same image after classifying it into three classes.

The PDD is an artificial image with cells having a value referring to the length of drainage ways in a specified neighbourhood of each cell. In this sense, the 'drainage density' image differs from the 'drainage network' image. It has to be clarified here that the term "drainage density" is not identical to the one used by geographers and geomorphologists. It is not based on the real drainage network; it is only derived from a digital terrain model. Therefore it does not take into consideration the loss of surface water due to infiltration into the soil. The potential drainage density is always higher or equal to the real drainage density of an area.

Figure 22: PDD image derived from a 90 m resolution SRTM DEM.
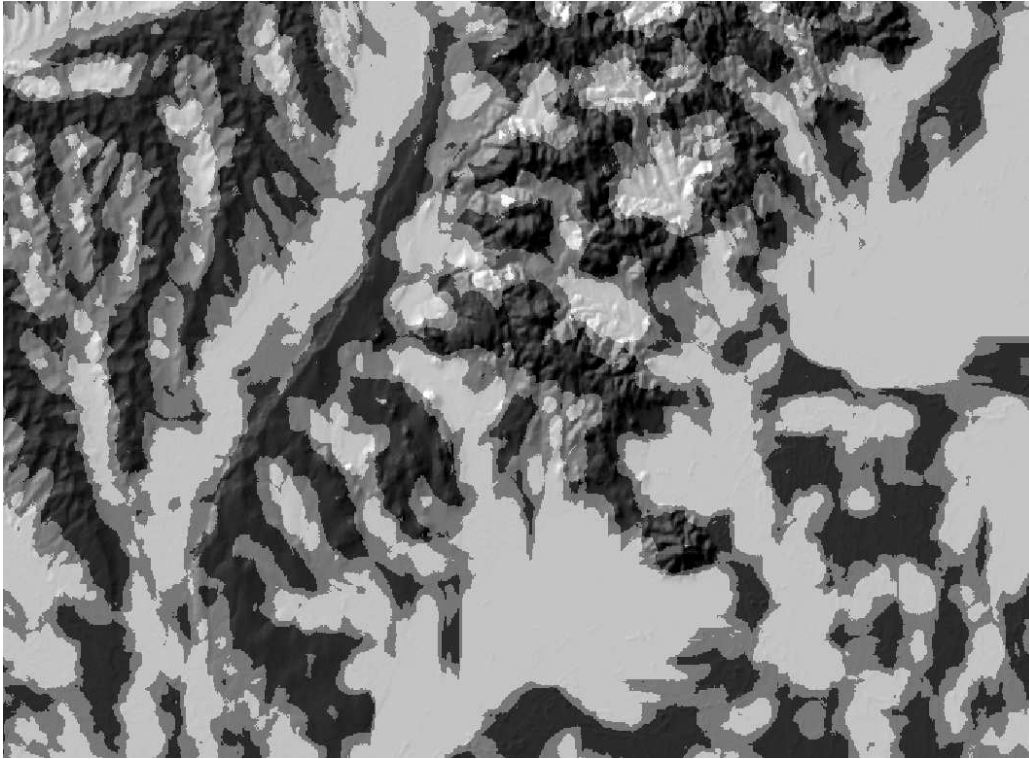
Figure 23: Classified PDD. Light colour refers to depressions and valley bottoms, intermediate colour to backslopes, and dark colour to ridges and local heights.

9. References

Dobos E., E. Micheli, M.F. Baumgardner, L. Biehl and T. Helt. 2000. Use of combined digital elevation model and satellite radiometric data for regional soil mapping. Geoderma. 97:367-391.

Dobos, E. 1998. Quantitative analysis and evaluation of AVHRR and terrain data for small scale soil pattern recognition. PhD. Thesis. Purdue University, West Lafayette, Indiana USA.

Jenson S. K. and J. O. Domingue. 1988. Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis, Photogrammetric Engineering and Remote Sensing. Vol. 54, No. 11, November 1988, pp. 1593-1600.

10. An Arc/Info® AML file to derive a PDD layer from a filled DEM.
 (AML can be created by copy/pasting the following text into a text editor and saving it to pdd.aml or can be downloaded either from http://support.esri.com/ > Downloads > ArcScripts or from http://eusoils.jrc.it/)
(see short documentation at end of AML)

```
/* PDD.AML
&echo &off save_echo
&args InAltGrid CatchmentAreaKm2 PddRadiusKm OutPddGrid rest:rest
&call ProgramInit


/* ***********************************************************************
/* ***********************************************************************
/* Main:

/* --------------------------------------------------------------------------
/* Convert catchment area threshold from km to number of cells:
&sv CatchmentAreaCells = [truncate [calc ( ( %CatchmentAreaKm2% * 1000 ) ** 2 ) / (
%grd$dx% * %grd$dx% ) + .5]]
&type Catchment area threshold converted from %CatchmentAreaKm2% km2 to
%CatchmentAreaCells% cells

/* Create drainage network layer:
pddtmp1 = con(flowaccumulation(flowdirection(%InAltGrid%)) >= %CatchmentAreaCells%, 1,
0)

/* Convert radius of the PDD moving circle from km to number of cells:
&sv PddRadiusCells = [truncate [calc %PddRadiusKm% * 1000 / %grd$dx% + .5]]
&type Radius of the PDD moving circle converted from %PddRadiusKm% km to
%PddRadiusCells% cells

/* Create PDD layer (as number of drainage cells within the %PddRadiusCells% moving circle):
&type Computing PDD...
%OutPddGrid% = focalsum(pddtmp1, circle, %PddRadiusCells%)
&messages &off
kill pddtmp1
&messages &on

/* Convert PDD from number of cells to km/km2:
&type Computing PDD in km/km2...
/** PDD holds the number of drainage cells within the %PddRadiusKm% circle.
/** The circle is (Pi * %PddRadiusKm% ** 2) km2:
&sv area = 3.141592 * %PddRadiusKm% ** 2
/** Each cell represents a drainage lenght of either the grid's resolution
```

```
/**   or its diagonal. Let's set it to an average of the two:
&describe %OutPddGrid%
&sv length = ( %grd$dx% + %grd$dx% * 2 ** .5 ) / 2 / 1000
/**  Each PDD value thus represents:
%OutPddGrid%km = %OutPddGrid% * %length% / %area%    /* km/km2


/* ------------------------------------------------------------------------
/* End of main:

&type Resulting grids:
&type  %OutPddGrid%: PDD expressed as cell counts
&type  %OutPddGrid%km: PDD expressed as km/km2
&call reset
&return


/* **********************************************************************
/* **********************************************************************
/* Standard program management subroutines:

/* ------------------------------------------------------------------------
/* Program initialisation:
&routine ProgramInit
&severity &error &routine error
&sv save_messages = [show &messages]
&messages &on

/* Debugging tool:
&sv debug off  /* set to on or off.
&echo &%debug%
&if %debug% = on &then &messages &on

&call ArgumentsControl
&return


/* ------------------------------------------------------------------------
/* Arguments control:
&routine ArgumentsControl

&if [show program] <> GRID &then &do
 &type This AML works only from Grid.
 &call error
 &end

&if [null %OutPddGrid%] or not [null %rest%] &then &call usage
```

48

```
&if not [exists %InAltGrid% -grid] &then &do
 &type Grid %InAltGrid% not found.
 &call error
 &end
&describe %InAltGrid%
&if %prj$units% <> METERS &then &do
 &type This AML works only on projected grids with units METERS.
 &call error
 &end

&if [type %CatchmentAreaKm2%] > 0 &then &call usage
&if [type %PddRadiusKm%] > 0 &then &call usage

&if [exists %OutPddGrid% -file] or [exists %OutPddGrid% -directory] &then &do
 &type File or directory %OutPddGrid% already exists.
 &call error
 &end
&if [exists %OutPddGrid%km -file] or [exists %OutPddGrid%km -directory] &then &do
 &type File or directory %OutPddGrid%km already exists.
 &call error
 &end

&if [exists pddtmp1 -file] or [exists pddtmp1 -directory] &then &do
 &type Temporary file or directory pddtmp1 already exists.
 &call error
 &end

&if [exists pddtmp2 -file] or [exists pddtmp2 -directory] &then &do
 &type Temporary file or directory pddtmp2 already exists.
 &call error
 &end

&return


/* ------------------------------------------------------------------------
/* Error management:

/* General error handling routine:
&routine error
&severity &error &ignore
&type Abnormal termination of program [upcase %aml$file%].
&call reset
&return &error

/* Usage:
```

49

&routine usage
&type Syntax error.
&type Usage: &RUN PDD <input elevation grid> <drainage area threshold (km2)>
&type   <PDD moving circle radius (km)> <output PDD grids prefix>
&type More help available from pdd.txt and pdd.doc.
&call reset
&return &error

/* --
/* Restore environment:
&routine reset
&messages %save_messages%
&echo %save_echo%
&return

/* **
/* **
/* Program and user documentation:

Joel Daroussin - JRC Ispra - 07/10/2004
Updated 20/12/2004: documentation.

AML built under ArcInfo 9.0 on PC.

--ASSISTANCE-
COMPUTES THE POTENTIAL DRAINAGE DENSITY (PDD) INDEX
FROM AN ELEVATION GRID.

Usage: &RUN PDD <input elevation grid> <drainage area threshold (km2)>
          <PDD moving circle radius (km)> <output PDD grids prefix>

Arguments:

  <input elevation grid> - Name of the elevation grid input to the procedure.
    Grid must be projected with units METERS.

  <drainage area threshold (km2)> - Threshold value in km2 used to initiate
    delineation of the drainage network.

  <PDD moving circle radius (km)> - Radius in km of the moving circle used
    to count drainage network pixels within the centre cell's neighbourhood.

50

<output PDD grids prefix> - Name of the output PDD grid. This first grid
   will hold counts of drainage network cells. A second grid named
   <output PDD grids prefix>km will be output to hold km of drainage
   network by km2.

Discussion:

For more details on the PDD index, please read pdd.pdf.

Notes:

. For better results consider using a FILLed -hydrologically corrected- input
altitude grid (see ArcInfo Grid command FILL for more information).

. Computing km of drainage network by km2 is a simple unit conversion process
neglecting diagonal versus horizontal (or vertical) lengths of drainage lines.
The lenght used is averaged from the straight and the diagonal lenghts of
cells.

References:
Dobos E., E. Micheli, M.F. Baumgardner, L. Biehl and T. Helt. 2000. Use of
   combined digital elevation model and satellite radiometric data for
   regional soil mapping. Geoderma. 97:367-391.
Dobos, E. 1998. Quantitative analysis and evaluation of AVHRR and terrain
   data for small scale soil pattern recognition. PhD. Thesis. Purdue
   University, West Lafayette, Indiana USA.

Monitor file for creating a SOTER Terrain Units polygon coverage generalized to the scale 1/5,000,000.

Joël Daroussin

To use this monitor file, open it into a text editor, then select the command (or set of commands) to execute, then paste it into a command prompt window. Commands are thus executed step by step under the user's control. The monitor file can easily be tuned to the user's own needs. For a full automation of the process, it can also be converted to an AML at the expense of slight adaptations.

```
/* 1 - Initialise:
/* The workspace must contain a raw SRTM DEM.

/* Launch ArcInfo:
arc

/* 2 - Fill the DEM:
grid
FILL dem demfill SINK 20


/* 3 - Compute the slope parameter grid:

/* Slope in %:
slope = SLOPE(demfill, PERCENTRISE)

/* Reclassify:
&data cat > slopeclass.txt
0 2 : 1
2 5 : 2
5 10 : 3
10 15 : 4
15 30 : 5
30 45 : 6
45 700 : 7
&end
slopeclass = RECLASS(slope, slopeclass.txt)

/* Block and resample:
slopeblock990 = BLOCKMAJORITY(slopeclass, RECTANGLE, 11, 11)
slopeclass990 = RESAMPLE(slopeblock990, 990)

/* Filter:
slope990filt4 = FOCALMAJORITY(slopeclass990, CIRCLE, 4)
```

```
slope990filt6 = FOCALMAJORITY(slopeclass990, CIRCLE, 6)
slope990 = CON(ISNULL(slope990filt4), slope990filt6, slope990filt4)


/* 4 - Compute the relief intensity parameter:

/* Relief intensity in m/(area of a 1 km diameter circle):
ri = FOCALRANGE(demfill, CIRCLE, 5)

/* Reclassify:
&data cat > riclass.txt
0 50 : 1
50 100 : 2
100 300 : 3
300 1500 : 4
&end
riclass = RECLASS(ri, riclass.txt)

/* Block and resample:
riblock990 = BLOCKMAJORITY(riclass, RECTANGLE, 11, 11)
riclass990 = RESAMPLE(riblock990, 990)

/* Filter:
ri990filt4 = FOCALMAJORITY(riclass990, CIRCLE, 4)
ri990filt6 = FOCALMAJORITY(riclass990, CIRCLE, 6)
ri990 = CON(ISNULL(ri990filt4), ri990filt6, ri990filt4)


/* 5 - Compute the potential drainage density (PDD) parameter grid:

/* PDD as drainage cells count:
flowdir = FLOWDIRECTION(demfill)
flowacc = FLOWACCUMULATION(flowdir)
drainage = CON(flowacc > 100, 1)
pdd = FOCALSUM(drainage, CIRCLE, 20)

/* Reclassify:
&data cat > pddclass.txt
1 90 : 1
90 1100 : 2
&end
pddclass = RECLASS(pdd, pddclass.txt)

/* Block and resample:
pddblock990 = BLOCKMAJORITY(pddclass, RECTANGLE, 11, 11)
pddclass990 = RESAMPLE(pddblock990, 990)
```

```
/* Filter:
pdd990filt4 = FOCALMAJORITY(pddclass990, CIRCLE, 4)
pdd990filt6 = FOCALMAJORITY(pddclass990, CIRCLE, 6)
pdd990 = CON(ISNULL(pdd990filt4), pdd990filt6, pdd990filt4)



/* 6 - Compute the hypsometry parameter grid:

/* Hypsometry in m is ready from the demfill grid.

/* Reclassify:
&data cat > hypsclass.txt
0 10 : 1
10 50 : 2
50 100 : 3
100 200 : 4
200 300 : 5
300 600 : 6
600 1500 : 7
1500 3000 : 8
3000 5000 : 9
5000 9000 : 10
&end
hypsclass = RECLASS(demfill, hypsclass.txt)

/* Block and resample:
hypsblock990 = BLOCKMAJORITY(hypsclass, RECTANGLE, 11, 11)
hypsclass990 = RESAMPLE(hypsblock990, 990)

/* Filter:
hyps990filt4 = FOCALMAJORITY(hypsclass990, CIRCLE, 4)
hyps990filt6 = FOCALMAJORITY(hypsclass990, CIRCLE, 6)
hyps990 = CON(ISNULL(hyps990filt4), hyps990filt6, hyps990filt4)



/* 7 - Build the raw SOTER Terrain Unit polygons:

/* Combine all 4 parameter grids to build a raster of major landform units:
physioraw = COMBINE(slopeclass, riclass, pddclass, hypsclass)

/* Filter to get rid of the insignificant salt and peper effect:
physiofilt = FOCALMAJORITY(physioraw, CIRCLE, 3)

/* Convert to raw SOTER Terrain Unit polygons:
soterraw = GRIDPOLY(physiofilt)
```

```
/* Each polygon is now a raw SOTER Terrain Unit. Give it a unique
/* identifiying number:
arc tables
dropitem soterraw.pat grid-code
additem soterraw.pat tu 4 5 b #
select soterraw.pat
calculate tu = soterraw# - 1
/* Distinguish universe polygon:
reselect $recno = 1
calculate tu = -1000
quit


/* 8 - Normalize the parameters needed for computing Euclidean distances:
/* Euclidean distances are computed between each polygon using the
/* raw, unclassified parameters grids slope, ri, pdd and demfill.
/* But to give each one an equal weight, they have first to be normalised.

/* Initialize looping:
&sv parameters = slope ri pdd demfill
&sv i = 0

/* Normalize loop starts:
&sv i = %i% + 1
&sv param = [extract %i% %parameters%]
&type normalizing %param%...
&describe %param%
&sv range = [calc %grd$zmax% - %grd$zmin%][unquote [extract %grd$type% .]]
%param%n = int(((((%param% - %grd$zmin%) / %range%) * 1000.) + .5)
&type done normalizing %param%.
/* Normalize loop ends.


/* 9 - Generalize polygons:
quit
&amlpath f:\daroussi\sotereurope\tools
&run generalize_polys soterraw tu soter5m mlf.dis similarity_distances 5000000 .2 25


/* 10 - Clean up workspace and end:
kill (!drainage flowacc flowdir hyps990 hyps990filt4 hyps990filt6 hypsblock990 hypsclass
hypsclass990 pdd990 pdd990filt4 pdd990filt6 pddblock990 pddclass pddclass990 physiofilt
physioraw ri990 ri990filt4 ri990filt6 riblock990 riclass riclass990 slope990 slope990filt4
slope990filt6 slopeblock990 slopeclass slopeclass990!)
quit
del *class.txt
```

55

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