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GEOREFERENCING AND QUALITY ASSESSMENT OF JOSEPHINE SURVEY MAPS FOR THE MOUNTAINOUS REGION IN THE TRIGLAV NATIONAL PARK

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Various spatial data sets of high quality and homogeneity allow a higher level of multidisciplinary research. The study is aimed at providing a clearer understanding of the technical and semantic aspects of the quality of historical maps, especially with respect to positional errors, through the georeferencing process. Georeferencing the system of historical map sheets with high precision over a large area is not easily incorporated into the less complicated standardised process. Significant problems may occur in rough mountainous regions, especially as many of the areas were not accessed at that time and therefore not surveyed. The standard process of georeferencing comprises mosaicking of singular map sheets to a seamless map, referencing with identical points, and applying an appropriate transformation method. The quality of georeferenced maps is assessed with statistical and visual parameters. The enhanced process additionally integrates descriptive (textual) information about the mapping processes, derivative georeferenced data sets as land use analysis, and Monte Carlo simulations. This approach allows a more detailed understanding of the quality and consequently improves a georeferencing process for any historical data sets. The First Military Survey maps of the Habsburg Monarchy (Josephine survey), produced between 1763 and 1787, were used as study data and the rugged Julian Alps of the Triglav National Park in Slovenia were employed as the study area.

Keywords: error simulation; georeferencing; historical maps; land use; quality control

1. Introduction

Maps are a presentation of the real world reduced to points, lines, and areas, using a variety of visual resources: size, shape, value, texture or pattern, colour, orientation, and shape. Compared to a photograph, which shows all visible objects in its view, a map is an abstraction of reality (Lanius 1999). The cartographer selects only that information essential to fulfil the purpose of the map and suitable for its scale; maps are a combination of science and art. The map's interpretation depends on a cognitive and semantic perception of the Earth by both the cartographers and the users.

The first presentations of the Earth's surface originated at least 30 000 years ago when people developed the ability to express themselves with symbols. Early maps were more figurative than literal and they were probably used mostly for ceremonial and ritual purposes (Robinson et al. 1995). The practical applications of ancient maps included aiding navigation, providing descriptions of places for hunting particular animals, marking directions of their movement, etc. Cartography was significantly advanced by Greek scholars who developed geometric concepts of the Earth. This tradition was continued and developed by Arab scholars during the medieval European era. The European renaissance in the sixteenth century further enhanced the development of cartography. Techniques applying the principles of mechanics, optics, chemistry, metallurgy, electromagnetism, electronics, etc. led to development of mapping and cartographic processes. For more effective presentation, geometrically and metrically correct presentations were demanded. It appears that the demand for land surveying arose from the need to measure the land for agricultural purposes beginning around five thousand years ago (Čeh 2002), and also on military requirements. These are the foundations of cartography as a science and technology.

1.1 Habsburg's military survey

After the end of the Seven Years' War against Prussia (1756–1763), which was lost due to the orientation problems in the unsurveyed area, a cartographical registration of the Habsburg Monarchy's crown lands was commissioned by the empress Maria Theresa (Grabnar 1994). The surveying lasted for twenty-three years (1763–1787) and resulted in 3 589 hand-drawn coloured map sheets (later expanded to 4 096) measuring approximately 61 by 42 cm, in a scale of 1:28 800. They covered the whole territory of the former Habsburg monarchy. The survey is known as the First Military Survey (MS1) of the Habsburg hereditary lands or the Josephine survey (Josephinische Landesaufnahme), because it was finished in the time of emperor Joseph II, Maria Theresa's son (Wawrik and Zeilinger 1989, Zimova et al. 2006). The maps were originally drawn in two versions — an original and a copy of fair quality. The copies are a bit bigger due to a frame that surrounds the map. This mapping and surveying was the first measurement of the whole territory of Slovenia (Triglav 2003).

A few framework points were astronomically determined (using the overview map), but the survey was not based on any use of triangulation (Kretschmer and

Riedl 2008). Furthermore, the survey was carried out without precise (geodetic) surveying measurements utilising a plane table and busole. Additionally, the existence of a cartographic projection is not clear. Some investigations suggest that the structure of the sheets is similar to a Cassini-Soldner (or Cassini, on the sphere) projection, but the others suggest that it is a projectionless map system (Timár 2004). Certainly the sheets do not hold any co-ordinates, whether of geographic or projection type. The generalisation methods are mostly unknown and varied but very likely depended on the importance of the particular feature or object to military needs. Most of the details were mapped with the unaided eye and their quality depends on the experience of the cartographer, his semantic comprehension, the variety of landscape characteristics, etc. This survey is, however, considered to be the most detailed and highest quality cartographical work until the end of the eighteenth century (Rajšp and Serše 1998).

The maps include the names of hills, valleys, and rivers written in local languages. Political borders are marked as well. Altitudes are presented with hatching to indicate relief. Distribution of forests and grasslands, directions of river currents, cultivated land, and other features are also mapped. The cultural landscape is presented by showing settlement type, buildings, roads, stone bridges, and even roadside shrines. The clarity of the maps is achieved through various colour casts. The sites of natural resource activities such as mines, saltworks, and iron foundries are not marked with symbols but rather with descriptive text. The size and format of the city names indicate their status (Rajšp and Serše 1998, Zimova et al. 2006, Gašperič 2007, Zorn 2007).

Although the First Military Survey is the focus of this study, a few subsequent efforts should be mentioned. The inadequate quality of maps from the First Military Survey led to new surveys in the nineteenth century by the emperor Francis II. After the foundation of the Austrian Empire (Kaiserstaat Österreich) in 1804, the 2nd survey of 1806–1869 was based on the first network of horizontal control points (triangulation). The Second Military Survey (Francis'), in scale 1:28 800, is considered much more accurate, as it is based on a geodetic and surveying foundation of good quality (Jenko 2008). Measurements of the triangulation networks were common for both land (Franciscan) cadastre and topographical maps (Korošec 1978). The centres of the geodetic networks (geodetic datums) for the separated co-ordinate systems on the territory of Slovenia were Krim (near Ljubljana, Slovenia), Schöckl (near Graz, Austria), and Gellért (near Budapest, Hungary). The triangulation of the Krim co-ordinate system that covered the larger part of modern Slovenia was carried out between 1817 and 1825 (Klarič 1975), but the military mapping was realised between 1830 and 1834 (Korošec 1978). The projection of the 2nd survey was Cassini, but was not precisely applied (Timár 2004). This is a transverse cylindrical projection, tangent and therefore equidistant along the central meridian. Relief was represented by Lehmann's hatching completed with heights of trigonometrical points.

After the 1860s, the rapid progress in geodesy, topography, and cartography initiated new approaches of topographical survey. The entire area of the Austro-Hungarian Monarchy (as to be named due to dualism since 1867) was mapped

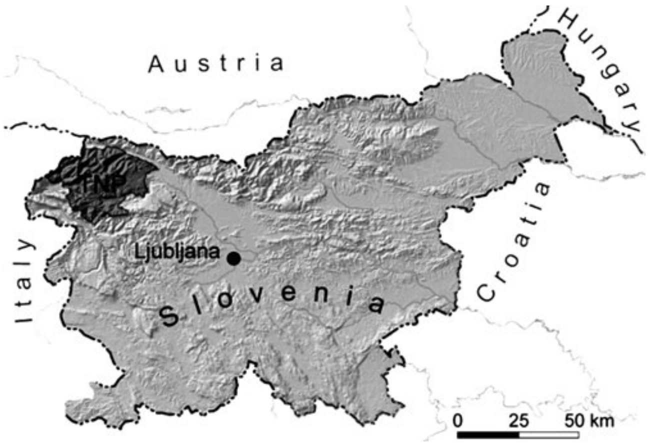

Fig. 1. Location of Triglav National Park (marked as TNP)

by the 3rd survey, based on the metric scale of 1:25 000 (and general maps in scale of 1:75 000) in only eighteen years (1869–1887), based on a new framework of horizontal and vertical control points in accordance with the standards of the Europäische Gradmessung. The 4th survey started in 1896, but was suspended in 1915 due to World War I (Kretschmer and Riedl 2008).

The military survey maps were not important to the general public as they were kept strictly as a military secret in the Military Archive in Vienna. With the opening of the archives, they have become an invaluable source for studies of historical landscapes. Increasing numbers of reprinted or scanned historical maps from different sources are available today (Rajšp and Serše 1998, NLS 2002, NUK 2008, ARS 2004, Podobnikar and Kokalj 2007). The usability of these maps could be significantly improved with georeferencing to allow more sophisticated spatial analyses in geographical information systems in combination with the other data sets.

1.2 Triglav National Park study area

The study area comprises the whole territory of Triglav National Park, the largest protected area in Slovenia, located in the northwest of the country (Fig. 1). The parks territory is characterised by the Julian Alps' heterogeneous rough relief with deep and steep, glacially transformed river valleys and gorges. Relief diversity and high elevation are the main factors for allocation of cultivable areas as well as settlement and communication systems. Most of the park is rich in various karst phenomena; limestone is the predominant rock type. Mountain ridges are an effective orographic barrier; the territory receives approximately double the average rainfall of the rest of Slovenia. High precipitation and steep slopes cause a number of landslides and avalanches. The park is characterised by richness of life with some rare protected flora and fauna (Podobnikar and Kokalj 2007).

The park bears important cultural heritage resources, including settlements with

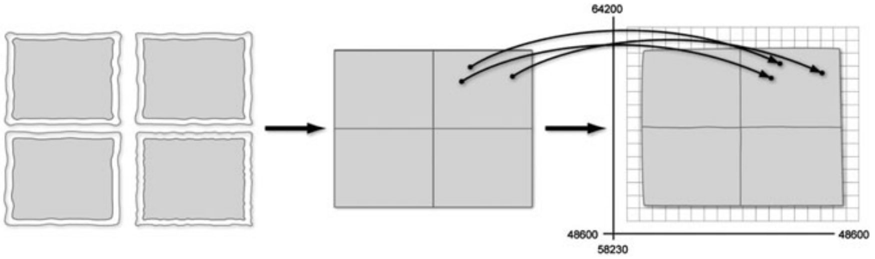

Fig. 2. Mosaicking and georeferencing of the MS1 maps

unique rural and sacred architecture; the historical remains of former ironworks; monuments to the memory of both world wars and to a battle of the Napoleonic period (at Predel); some notable archaeological sites; remarkable traditional mountain pastures; and a populace with rich traditional knowledge and proficiency gained from centuries of observation and living in nature (Podobnikar and Kokalj 2007).

2. Mosaicking and georeferencing of the military survey maps

Georeferencing of a number of MS1 historical maps of a rough mountain region of Slovenia was carried out with the following procedure (Fig. 2):

- mosaicking – relative georeferencing of the individual map sheets to the dependable position of the previously generated grid and stitching them seamlessly into a cohesive map,
- georeferencing to a contemporary Slovenian co-ordinate system.

2.1 Mosaicking

Mosaicking is a process of stitching the images, in our case maps, together into one large, coherent map of the studied area. The principle of mosaicking the MS1 maps is based on the requirements that particular map sheets should be rectangular, resembling their original shape with dimensions of 61 by 42 cm, and that they should meet seamlessly along the edges. This was achieved by constructing a grid system (sheet network) representing the ideal original positions of the maps, cropping the edges without cartographic content, setting reference points to the edges of the map sheet network, and fitting the maps using rubber sheeting. The advantage of this technique was to prevent greater distortions (gaps and overlaps) at the borders of the map sheets within the mosaic (Fig. 3). As not all borders of the scanned maps are straight, some small geometrical corrections were applied around them using georeferencing methods on additional identical points.

The next step is colour balancing, a process of inconsistent colour cast homogenisation. The colour cast can be a result of imprecise scanning process or, more commonly, an outcome of the original print. Because different cartographers produced the maps, their overall colour cast differed originally and has increased over the centuries due to aging. Colour balancing computes a global statistics across each

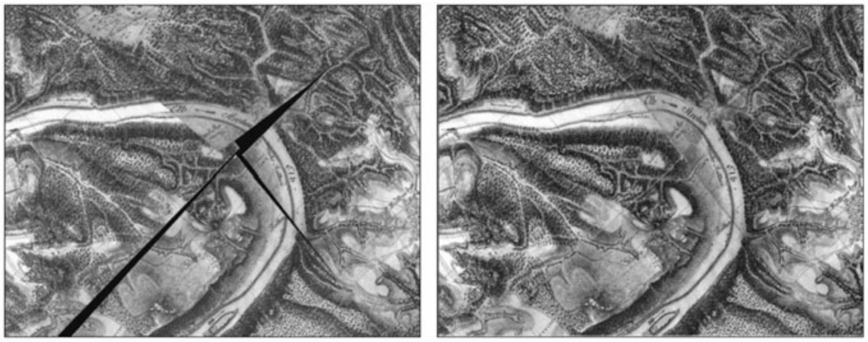

Fig. 3. Left: Distortions at the map sheet borders of the single map sheets and a mosaicking afterwards. Right: prevention of distortions using rubber sheeting technique (Walz and Neubert 2005)

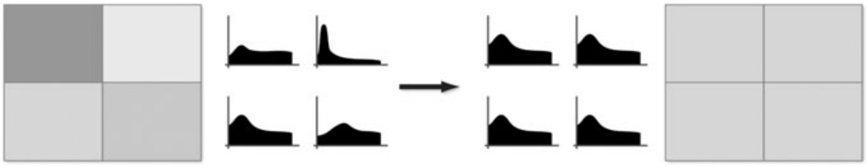

Fig. 4. Principles of mosaic colour matching

map in the mosaic in order to smooth out light imbalances. Certain very bright or dark areas can be avoided in order not to degrade the statistics. The method used to compute the statistics in each map depends on the distribution of the colour difference. This can be either parabolic — the colour difference is elliptical and does not darken at an equal rate on all sides, conic — the colour difference will peak in brightness in the centre and darken at an equal rate on all sides, linear — the colour difference is graduated across the map, or exponential — the colour is very bright in the centre and slowly, but not always evenly, darkens on all sides. Using histogram matching, to either a single map (the map that contains the colour characteristics we would like to see in the mosaic) or an ideal combined histogram, colour and brightness of the input maps are matched on the mosaic (Fig. 4).

The last step was manual — visually removing the remaining local anomalies along the edges of the mosaicked map sheets using digital brush tools. The final product resembles a single seamless cohesive map. It should be noted that the colour balancing and manual removing of the anomalies are not essential for the vectorisation of land use information from the maps, but it increases the precision of interpretation and is important for a powerful visualisation of the studied area.

2.2 Georeferencing

Transformation to the target co-ordinate system is the main goal of georeferencing the historical maps. Two methods of georeferencing may be distinguished: transformation between two co-ordinate systems where transformation parameters are known, and transformation using identical ground points where transformation parameters are unknown. The techniques for georeferencing depend on the characteristics of the historical MS1 maps: the quality of the geodetic grids, the map projections, generalisation methods, etc.

The possible map projection of the MS1 was Cassini-Soldner, that is, an ellipsoidal version of the Cassini projection for the sphere. It is not conformal but is relatively simple to construct. It was later largely replaced by the conformal Gauss-Krüger or Transverse Mercator which it resembles. Like this, it has a straight central meridian along which the scale is true, all other meridians and parallels are curved, and the scale distortion increases rapidly with increasing distance from the central meridian.

If the original projection is known and precise, the map sheets can be projected using unique transformation parameters, with projection parameters including a central meridian and the shape of the map sheet (four points at the edges). Projection error rises if a meridian convergence is not taken into account (Korošec 1993). This method can be applied on a small scale for low accuracy (or coarse) transformation (Podobnikar and Šinkovec 2004). The Second and Third Military Surveys were so precisely mapped that the unique transformation parameters could be obtained for a larger area with relatively high precision. The maps of the Second Military Survey have been successfully transformed to a contemporary map grid for the entire ancient Habsburg territory (Timár et al. 2006). This method was also successfully accomplished for the land cadastre sheets mapped in the Krim co-ordinate system, transformed with higher precision to the Slovene Gauss Krüger co-ordinates. For the territory of Slovenia, many studies have been available on these transformation parameters since the 1960s (Klarič 1975, Frančula and Lapaine 2007, Lapaine 2008, Jenko 2008).

In the case of the MS1, there were many uncertainties in mapping, especially with uncertain distortions in the rough mountain area, as described earlier. The georeferencing was carried out without known parameters by 1. using reference data sets, 2. finding identical points, and 3. applying an appropriate transformation method. Orthophotos or topographic maps of scale 1:25 000 were used for the reference data sets then mapped onto a contemporary Slovenian co-ordinate system.

Identical points should be located on geographically identical positions of the MS1. They should be chosen very carefully. Potentially the best points are the measured ones: churches or towers. To locate appropriate points, it is important to note the "style" of a particular cartographer and cartographic elements, including the level of generalisation of the maps. Additionally we should be very attentive to possible landscape changes and aware that at the time of the mapping the highest peaks in the Julian Alps had not yet been scaled, and most of areas had not been reached yet (Podobnikar and Kokalj 2007).

The chosen identical points in the MS1 used for georeferencing were: churches (especially those on the peaks), characteristic bridges, road crossings, towers, and occasionally, distinguishable summits or rivers' confluences (Podobnikar and Šinkovec 2004, Podobnikar and Kokalj 2007). Very rough mountain terrain prevented selection of a greater number of reliable identical points (Fig. 5). Only around 190 identical (ground) points were found for the whole Triglav National Park study area.

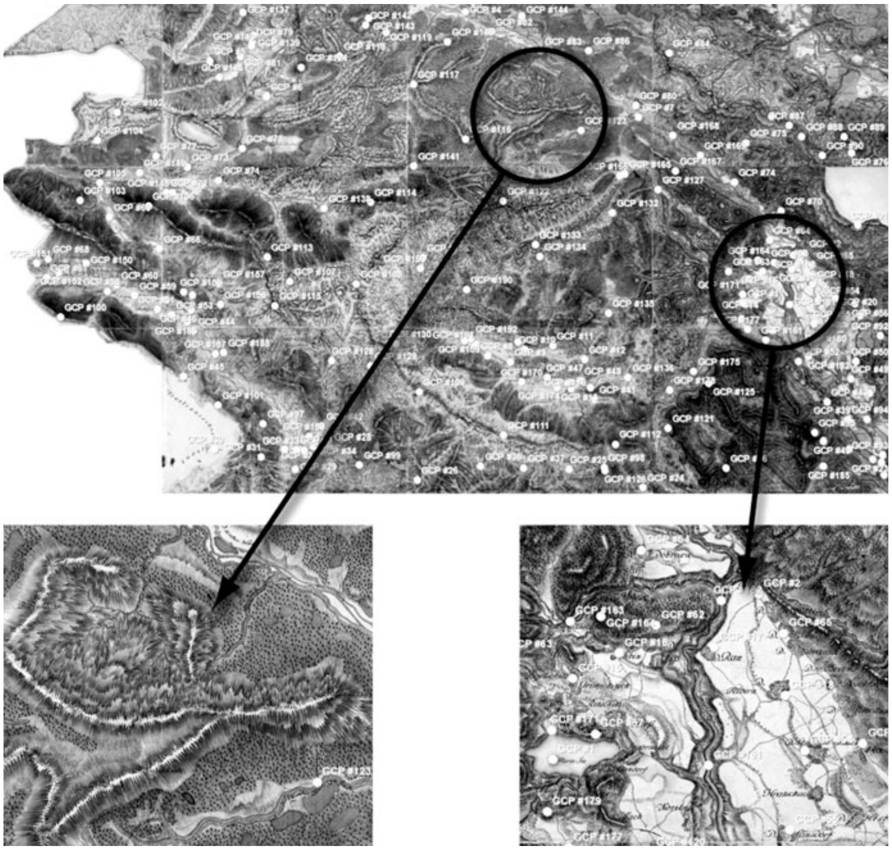

Fig. 5. High mountain areas often lack confident reference points of any kind

The third step of georeferencing with unknown transformation parameters is applying the appropriate transformation method for transformation to a contemporary Slovenian co-ordinate system, based on the Gauss Krüger (UTM) map projection. Classically we can choose between the common transformation methods using approximation with polynomials or with rubber sheeting (based on triangulation where the position of the identical points remains after the transformation). The polynomial order 1 is appropriate for transformation between two projections where great distortion is not present (useful for transformation between newer maps). The polynomial order 2 is appropriate for transformation between geographical co-ordinates (or sphere) and projected data, or for locally systematically distorted data sets in larger areas (e.g. for mountain areas or for aerial photographs). The rubber sheeting method could be more useful on more highly distorted areas, but it requires a high number of identical points. Unpredictable distortions could appear around areas of deficiency. In our case a rubber sheeting method was chosen as optimal for the MS1 maps. A classical assessment for the measurement of transformation accuracy is a root mean square error (RMSE).

Considering the transformation methods, a simple test would be applied to the maps to determine the projection nature. We mentioned in the previous paragraph that the polynomial transformation order 1 is appropriate for the transformation between two projections lacking significant distortion. As the Cassini and Gauss Krüger (UTM) projections are similar, a low RMSE would be expected after the transformation. Unfortunately, this method is not suitable for the MS1 maps as the local distortions (errors) are too large.

3. Land use data acquisition and interpretation

Topographic maps and their predecessors, produced in land surveys since the eighteenth century, provide a suitable cartographic base for historical landscape analysis. They have sufficient resolution in terms of geometry and content for medium-scale studies, enabling landscape development over the past two hundred years to be investigated (Haase et al. 2007). A rather rapid descriptive comparison can be made when considering elements of the maps such as the transportation network (a comparison of historical and contemporary courses of roads and paths, density of network, types of connections, the number and locations of bridges), water courses and their regulations, settlements (routes of roads and streets in settlements, expansion of settlements and changes in structure), and the distribution of vegetation.

Employing land use information from the MS1 maps and comparing it with the contemporary data sources is a common application of the series studies. Some of the significant ones are listed here. The interpretation over the territory of Slovenia is based on the scanned reproductions. The studies of interest to historians were published together with the maps by Rajšp and Serše (1998). Geographers Ravbar and Prelovšek (2005) analysed historical land use of the Udin boršt area, and Zorn (2007) studied the usability of the MS1 as a geographical source. Several attempts were made to georeference the MS1 data and analyse them in geographical information systems. A number of analyses were generated by Podobnikar and Šinkovec (2004); changes of the Ljubljanica river course together with the Gruber channel, and railways in Ljubljana were detected and mapped as a time-series using numerous georeferenced maps and orthophotos. Kušar and Hočevar (2005) analysed the MS1 map sheet near Kranj as a source for determination of changes for forestry studies. Using various historical maps together with satellite images, Timár et al. (2008) analysed watershed and geomorphological changes in the Banat region (Hungary, Romania, Serbia).

The results of these studies show that the interpretation of MS1 maps is far from simple. The areas that were most easily interpreted in the studies are rivers, roads, built up areas and forests. This element of study is additionally important for enhancing information about the maps quality in order to control and improve the georeferencing. This is accomplished by distinguishing the positional accuracies of the particular mapped features (e.g. positions of churches vs. borders of forests). It also aids understanding of which features or which areas might have significantly changed since the production of the MS1 (e.g. position of churches vs. river beds).

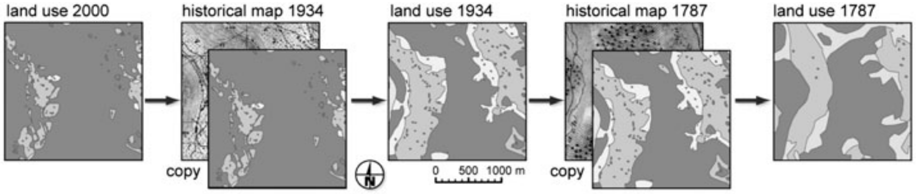

Fig. 6. Backward editing method. Note that the label "historical map 1787" denotes the MS1 maps

3.1 Land use data of the MS1 maps

We propose our own solution using the MS1 maps in the Triglav National Park. The land use classification was rearranged into fourteen classes based on the contemporary land use data set, resembling the Corine land cover nomenclature. The majority of classes were distinguishable in the entire set of historical maps ranging from the MS1 to contemporary ones, though in some cases, just barely. For better categorisation, additional information was used: the shape of relief, aspect, proximity of urban areas, the increasing elevation of the upper vegetation level during the last decades, and the general order of vegetation zones. Land use data was acquired by a backwards editing method — map-by-map (Fig. 6), starting with the contemporary vector-based land use data (Walz and Neubert 2005).

Analysis of the textual material and land use spatial data focused on processes such as grassing, afforestation, changes in population, industry and tourism, and the effects of the World War I Soča (Isonzo) Front in order to interpret the land use changes. Statistical and visual analysis of the land use maps thus produced revealed that non-forest categories constituted the largest land use type in the beginning of the nineteenth century and that the percentage of forest has been growing ever since to reach today's 63%. Besides farming, ironworking and its associated activities were the main economic activities in Triglav National Park at the turn of the nineteenth century. Firewood requirements for charcoal and intensive high-mountain grazing had reduced the forest and lowered the natural timberline (Valenčič 1970, Petek 2005). The forest is now recapturing its natural territory with the collapse of ironworking and near abandonment of grazing.

Grassing was another prominent process, emphasised by the decline of agriculture caused by the introduction of railway and industrial activities near the park at the end of the nineteenth century. People working on small farms but forced to migrate to work in non-agrarian activities due to economic need were given a special name — half-farmers (Klemenčič 1974). They have been an important factor in cultural landscape preservation. Afforestation and grassing have been reduced recently by greater support of agriculture and development of tourism (Podobnikar and Kokalj 2007).

The surface extent of built up areas has been growing slowly, but steadily, since the end of the nineteenth century onward. This observation contrasts with textual sources, where we find that in the period after World War I the area faced depopulation. Migration was more prominent on the western side of the park (Trošt 1966), while some settlements in Bohinj grew significantly (KLS 1995).

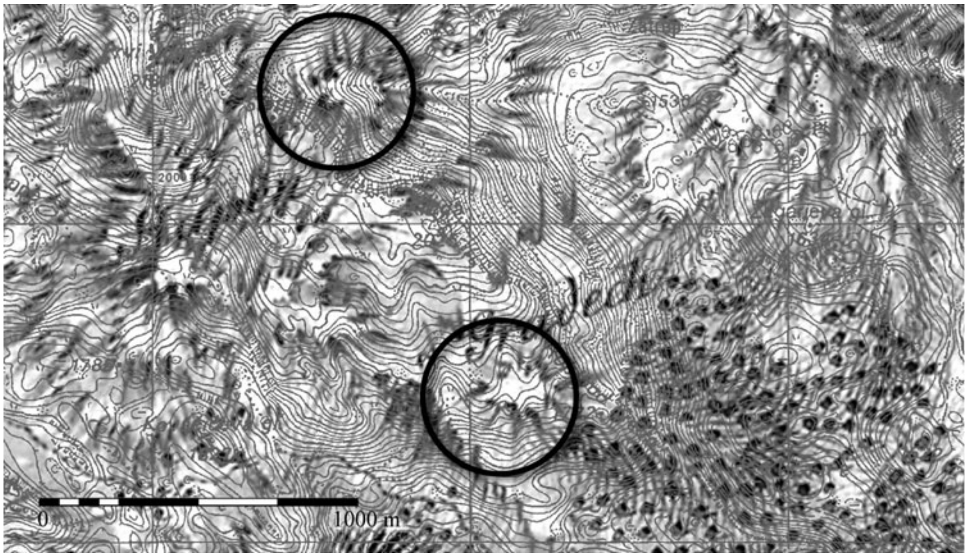

Fig. 7. Lack of knowledge and surveying of the mountain environment lead to an imaginative interpretation of the relief surface. Mountain peaks that do not actually exist can be seen by comparing the MS1 map and overlaid contemporary contour lines

4. Quality assessment and error simulation

The quality assessment was monitored through the following methods: obtaining an *a priori* knowledge of the MS1 maps; learning about cartography methods through the visual appearance of singular map sheets; trying to find rules of mapping by means of mosaicking the map sheets; studying similarities of the mapped features to contemporary conditions for defining the position of reference points; georeferencing the MS1 maps in comparison with contemporary data sets; preparing an object catalogue for land use studies, and interpretation of the land uses, etc. We proved the findings of Korošec (1993) that the relief representation of the higher and rocky areas of the Julian Alps in the MS1 maps is not only a coarse approximation, but also unconvincing and unreal. Elevation data were not considered at the time of the survey, resulting in false relationships of geomorphology (Fig. 7).

The aim of the quality assessment is to analyse the quality and errors that can occur in the MS1 maps by:

- statistical tests (and visualisation) of the possible errors, and
- simulation of the errors.

Both approaches apply a quality assessment that includes identical points from historical maps and from reference data sets as well as the vectorised land use data sets. Simulation also involves other information gathered as part of *a priori* knowledge (e.g. common problems of Habsburg's military survey).

Table I. Positional and thematic accuracy evaluation for the MS1 maps. RMSE was tested with 190 control points (in mm as appeared in the maps and in m on the terrain) and AME with 16 control points. PCC was tested for the following categories: urban fabric, forest, grassland, and "all the others", as listed

Accuracy (type)	Error (type)	Error (value)	
Positional	RMSE (190 pts.)	16.7–19.1 mm	480–550 m
	AME1	(16 pts.) 19.8 mm	570 m
	Max.	36.5 mm	1050 m
	AME2 (10 pts. – peaks	5.5 mm	160 m
	10 pts. – streams)	13.5 mm	390 m
Thematic	PCC	45%, 79%, 67%, 79%	
	Kappa	0.67	

4.1 Quality assessment in MS1 maps

The quality of the land use data interpretation is affected by the positional and thematic accuracy of the georeferenced MS1 maps. The following positional accuracy parameters were evaluated (Table I):

- Root mean square error (RMSE) was evaluated for polynomial transformations order 1 and 2 through georeferencing (a rubber sheeting method does not produce the RMSE as the position of the identical points is kept after the transformation; Podobnikar 2008).
- Averaged maximum error (AME1) was calculated as differences between manually selected control points on georeferenced maps (the georeferencing method is less important in this case) in comparison with reference data sets (locally maximum deviations were chosen); it is a control for RMSE.
- Averaged maximum error (AME2) was calculated according to rubber sheeting transformation. As the identical points for the rubber sheeting already employed churches, bridges, some peaks, and road crossings, ten randomly (but significant) points on peaks and ten points on streams from the MS1 maps were compared with the reference data sets. For the most part, the error signifies local systematic errors on primarily flat areas. The results are therefore an underestimation of error.

The thematic accuracy was evaluated using (Table I):

- Proportion correctly classified (PCC) as a proportion of agreement between the reference and the MS1 data sets.
- Kappa coefficient as a measure of agreement between two binary variables. A Kappa value higher than 0.60 is usually interpreted as a suitable agreement (Giordano and Veregin 1994).

The final result of georeferencing is less accurate than results from comparable studies (Kušar and Hočevar 2005, Zimova et al. 2006, Haase et al. 2007) due to the prevailing rugged alpine relief in Triglav National Park.

4.2 Simulation of positional error of the MS1 maps

The quality assessment based on evaluation of positional errors, calculated with different methods and on the basis of various transformations, better indicates the nature of the errors than previous steps of analysing the data. The main source of the errors lies in mapping the MS1 maps, and secondarily on the derived (vectorised) land use data set (land use borders are positionally less precise than the control points used for transformations). The simulation of the errors can assist in understanding the nature of the errors, and improving techniques for georeferencing, and, in a next iteration, improving the simulation.

Monte Carlo simulation is a known statistical method for computation with random numbers. Multiple realisations are often needed because every simulation is just one of a large number of representations of a specified probability model (Haining 2003). The idea of stochastic simulation is to develop a spatial Monte Carlo model — a generator that enables creation of many equally probable realisations of a random function/field.

Local probability density functions are used to developing a probabilistic model for a random variable at any point in space. A transformation of the uniform distribution of discrete random variable to normal distribution can be applied by the Box-Muller method. A general procedure for the Monte Carlo simulation algorithm is (Podobnikar 2008):

- generate a set of random numbers $i = 1, \ldots, m$ dependant on a specific model,
- for the current set compute appropriate (conditional) distribution and store individual output,
- repeat the upper procedure N times, and
- compute and store sample statistics from the N outputs.

The number of simulations depends on objectives of the study and the phenomena surveyed. Monte Carlo methods of error analysis are usually followed by a statistical theory of error distribution and propagation (Burrough and McDonell 1998). Land use data sets based on the MS1 maps were simulated with the following assumptions (Podobnikar 2008):

- random (mostly relative) effects: instruments, human factors, and others that are undefinable with respect to precision;
- locally systematic (mostly relative) effects over larger areas that could also be classified as spatially smooth or random on a smaller scale: triangulation errors, errors in measurements of long distances, avoiding obstacles, absence of measurements, other undefinable errors, distributed as described; and
- systematic/gross (mostly absolute) effects over the whole case study area: projections, measurements.

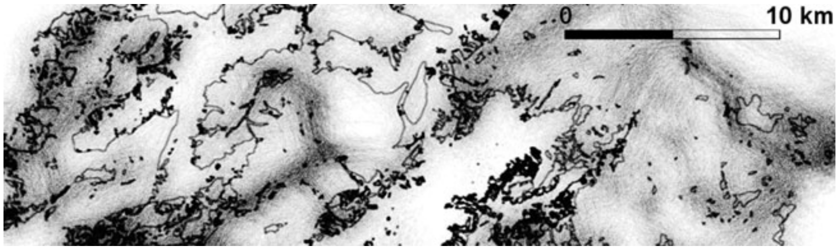

Fig. 8. Land use data acquired from the MS1 simulated $N = 100$ times with the Monte Carlo method using the land use boundaries for that part of the Triglav National Park. Distributions of the borders show possible error expanses. Some are less diffuse than others depending on the accuracy of the land use with σ applied

Simulation of the first error type is the most simple. The second and third errors are not so easy to simulate, especially with respect to systematic or even gross errors that are most probably not distributed randomly, but their nature is sometimes similar to stochastic. Nevertheless, because of inexact and uncertain classification of error types, we tried to simulate all three groups.

The first step was to create random values with standardised unconditional Gaussian distribution, mean value 0, and standard deviation 1. Those distributions were transformed conditionally regarding measured and evaluated RMSE values that present standard deviations of simulations.

4.3 Vector boundary simulation — first principle

The Monte Carlo error simulation was applied using two different approaches. The first followed the rules of boundary simulations (Burrough and McDonell 1998). Land use boundaries acquired from the MS1 were assigned values of measured RMSE. The average σ value is 17.9 mm $\cdot$ 28 800 = 515 m (Table I). This assumption exaggerates the reality in the flat areas (e.g. along the most populated areas in Bohinj significant error is not expected), for more precisely measured churches and road crossings, and along the areas enhanced with more precise data sources (less diffuse borders of the highest possible vegetation occurrence in Fig. 8), but it matches well the error in the rough mountainous relief (very diffuse borders in Fig. 8). However, although this is a large error, we could not reduce the RMSE in this region as additional control points could not be located on the map. Additional uncertainty of the σ determination was simulated with σ_1 around σ, where $\sigma_1 \ll \sigma$. Furthermore we ensured that the shape of the particular simulated object remained similar to the acquired original. After applying that condition the neighbourhood nodes of the boundary lines are correlated (Podobnikar 2008).

The second approach of the first principle was identical to the first, with the exception that simulation was applied to boundaries of polygons (not lines). In order to preserve original topology as much as possible, the proper solution of this simulation is much more complex (Podobnikar 2008).

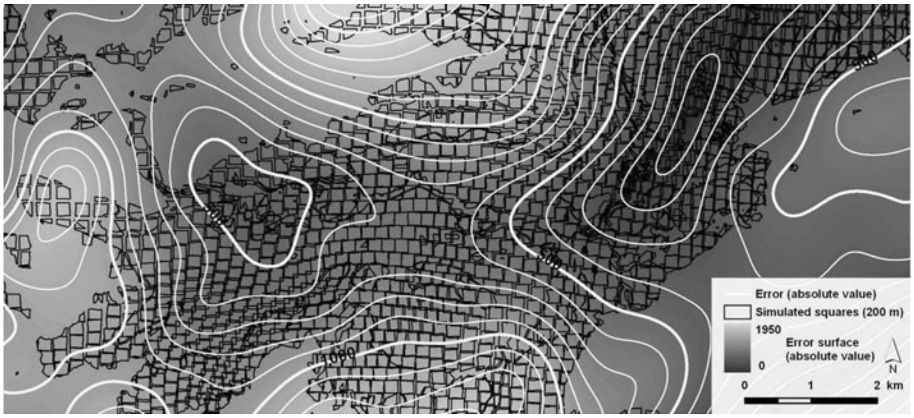

Fig. 9. One of the Monte Carlo simulations of selected land uses from the MS1. A random distribution surface represents absolute values between co-ordinates shifted in the x and y directions. Brighter areas mean larger shifts. Contour lines support shaded surface — higher density lines represent conversion between different locally systematic errors. The autocorrelated arrangement of square polygons with 200 m sides presents possible distortions of the land use data due to shifts. The local systematic error is constant where squares are connected; elsewhere it is changing. The individual land use areas are therefore continuously deformed and shifted. Little or no random error is expected within the square boundaries

4.4 Continuous surface simulation — second principle

With continuous surface simulation the error is simulated for the areas of the land use data and not just for the borders. This procedure can provide better understanding both of what was simulated and of other possibilities applied to the simulated error model. The main idea is that the greatest part of error distribution in the mountainous area is locally systematic and can be suitably represented by a random autocorrelated (continuous) surface. For locally systematic error distribution we assumed a spatially smooth distribution. Locally shifted homogenous areas were simulated (e.g. one valley, one settlement) in relation to imprecise measurement between selected areas, but with higher precision inside them (Podobnikar 2008). The problem and appearance of this error is similar to residuals of the (seven-parameter similarity) transformation parameters between the national co-ordinate systems and the European (more global) ETRS89 (e.g. Stopar and Kuhar 2003).

The same principles were used to apply a more spatially rough error that approximates the more random (or locally very thin) distribution related to measurements on short distances. This error distribution is somewhat similar to the first principle, but instead of lines, small areas are simulated (Fig. 9, Podobnikar 2008). Both artificial randomly autocorrelated surfaces were generated as standardised unconditional Gaussian distributions with mean value 0 and standard deviation of 1. A Moran I measure was used to achieve the required degree of autocorrelation. The same procedure was performed for the smooth and rough random surfaces, but with different spatial resolution. Similar to the first principle, the evaluated RMSE value ($\sigma = 17.9\ \text{mm} \cdot 28\,800 = 515\ \text{m}$) was annotated to the standardised complex surface.

The next stage involved attributing the shifts in the x and y direction considering complex error surfaces. The shifts were applied to the land use data set acquired from the MS1 map. To apply the shifts, two approaches were followed. The first was tessellation of land use into uniform square areas (vector polygons) with 200 m sides. This approach was combined with the first principle, so boundaries of the polygons were simulated for all squares (Fig. 9, Podobnikar 2008). Thus we can effectively simulate error distribution considering all three listed presumptions: random, locally systematic, and systematic/gross errors. The second approach is similar to the first, but squares were replaced with denser grid points to simulate grid-based land use surface.

5. Conclusions

Georeferenced historical maps allow an effective multidisciplinary spatial analysis in geographical information systems in combination with other georeferenced and descriptive data sets. High precision georeferencing of the system of historical map sheets covering a large area is a difficult task. Even greater problems may occur in rugged mountainous regions, especially in cases where most of the area was not accessed and therefore not surveyed.

The main problems that occurred during the georeferencing process of the Habsburg Monarchy 1763–1787 MS1 maps were: poor geometry (big and nonhomogeneous distortions) of the mapping, unknown (undefined) co-ordinate system, low quality surveying equipment that generated various errors, oversimplified mapping and generalisation techniques, changes of the landscape since the time of the mapping, the very narrow military purpose, inexperience of the surveyors, low standardisation that allowed a great deal of subjectivity, etc.

Advantages of our georeferencing approach include: deep and precise study of the maps of MS1; study of different techniques of the transformation in combination with finding as many identical points as possible; improving the georeferencing with the study of the accuracy parameters of the vectorised land use data; comparison between the identical points and land use data set that was enhanced with a time-series analysis; and quality control of the transformed data with evaluation of the positional and thematic accuracy by applying Monte Carlo simulation techniques — by trying to approximate the real errors that occurred on the MS1 maps. The described approach helped the understanding and avoidance of the problems of georeferencing (detailed in the previous paragraph). This integrated methodological approach enables improving the positional accuracy of the MS1 maps in a step-by-step empirical way.

According to Rajšp and Serše (1998) the value of the MS1 maps lies especially in their content: topographical names, road connections, and other information important to increasing our knowledge of the cultural landscape, whereas the accuracy of these maps is unfortunately not their greatest value. Our research demonstrates that precise georeferencing significantly enhances the value of these maps, especially in combination with any other spatial data sources within the geographical information system.

Usability of any (spatial) data set could be increased with a careful quality assessment that includes standardised and well-known procedures (e.g. according ISO standards), and additionally, procedures adjusted to a specific problem as shown in this paper. Another important step after studying the particular data sets is preparing the metadata information and enabling their effective accessibility for wider use, which can comprise various interdisciplinary studies on the historical data sets.

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