

Application of Geographical Information System in archaeology. A topography reconstruction of the medieval palatium in Ingelheim

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Introduction

The palatium in Ingelheim [Ger. *Kaiserpfalz, Pfalz*] was situated in the middle terrace of the Rhine in the eastern part of the current municipal area (Germany, Rhineland-Palatinate, Fig. 1). According to historical sources, the beginnings of the residence date back to the end of the 8th century. It was founded by Charlemagne (747/748–814), also known as Charles the Great. He visited this place in 787 and 788 for the first time, which is mentioned by Einhard, the ruler's chronicler¹. The main expansion of the residence took place during the reign of Charlemagne and his successors. At that time the two largest architectural constructions were built, namely the aula regia and the north hall. Then the exedra, a semi-circular building with a columned passage, was probably completed as well. The north and south borders of the palatium were also determined as two parallel sec-

tions. The church with its three apses was built in the central part of the foundation² (Fig. 2). Charlemagne as well as his heirs appreciated this place, e.g. Louis the Pious visited the palatium in Ingelheim about ten times³. Another period of the residence's expansion is associated with the reign of two dynasties, namely Ottonian and Salian. During that period the palace ex-



Fig. 1. Map of Germany and the location of the city of Ingelheim

¹ H. Grewe, *Geschichte und Neubeginn der archäologischen Forschung in der Königspfalz zu Ingelheim am Rhein*, „Acta Praehistorica et Archaeologica”, 30, 1998, pp. 181.

² H. Grewe, *Geschichte und Neubeginn*, pp. 177–178; H. Grewe *Die Königspfalz zu Ingelheim am Rhein*, in: Ch. Stiegemann, M. Wemhoff (eds.), 799 – *Kunst und Kultur der Karolingerzeit*, vol. 3, Mainz 1999, pp. 145–148; H. Grewe, *Die Ausgrabungen in der Königspfalz zu Ingelheim am Rhein*, in: L. Fenske, J. Jarnut, M. Wemhoff (eds.), *Deutsche Königspfalzen. Beiträge zu ihrer historischen und archäologischen Erforschung*, vol. 5: *Splendor palatii. Neue Forschungen zu Paderborn und anderen Pfalzen der Karolingerzeit*, Göttingen 2001, pp. 158–168; H. Grewe, *Die bauliche Entwicklung der Pfalz Ingelheim im Hochmittelalter am Beispiel der Sakralarchitektur*, in: C. Ehlers (ed.), *Deutsche Königspfalzen. Beiträge zu ihrer historischen und archäologischen Erforschung*, vol. 7: *Zentren herrschaftlicher Repräsentation im Hochmittelalter: Geschichte, Architektur und Zeremoniell*, pp. 104–106; U. Wengeroth-Weimann, *Die Grabungen an der Königspfalz zu Nieder-Ingelheim*, Ingelheim 1973, pp. 14–22 (Beiträge zur Ingelheimer Geschichte, vol. 23).

³ H. Schmitz, *Pfalz und Fiskus Ingelheim*, Marburg 1974, Appendix (Untersuchungen und Materialien zur Verfassungs- und Landesgeschichte, vol. 2).

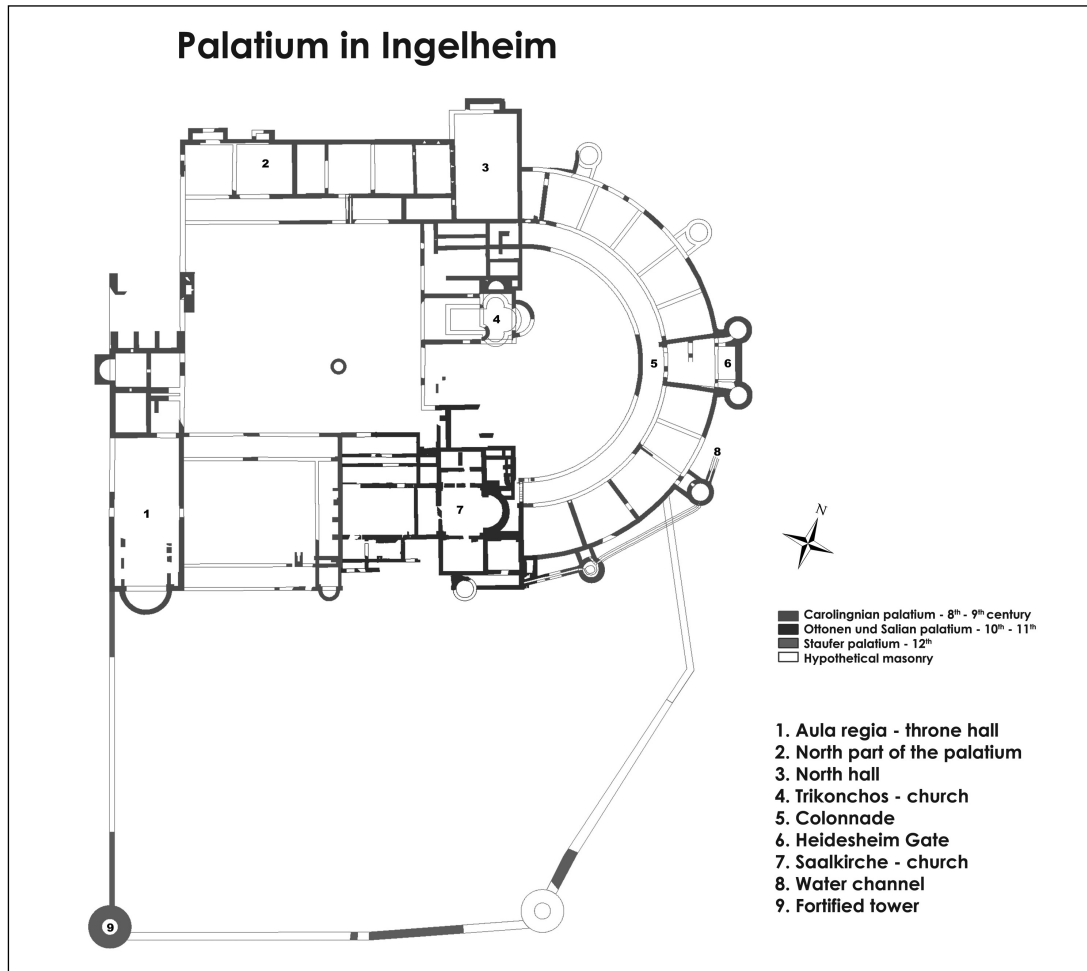


Fig.2. Palatium in Ingelheim, the building phases and the main constructions

perienced its architectural renaissance. Limited transformations were accomplished inside particular buildings and larger changes were related to the sacral architecture. The church Saalkirche (a church in an architectural cross form) dates back to the second half of the 10th century. The earlier sacral place of the residence represented an inconsiderable church with three apses in the middle of this foundation which was rebuilt into a slightly larger one-apse chapel probably in the 9th century⁴. The changes made in the Staufer period at the beginning of the 12th century were the next very important stage of the palace's development. At that time the southern part with the surrounding walls was built and

the residence took on a defensive character⁵. In the 14th century the palace lost its residential character and was transferred into the hands of the Order of Saint Augustine by Charles IV⁶. During the Thirty Years' War the buildings of

⁴ H. Grewe, *Die bauliche Entwicklung*, pp. 102–107.

⁵ H. Grewe, *Visualisierung von Herrschaft in der Architektur. Die Pfalz Ingelheim als Bedeutungsträger im 12. und 13. Jahrhundert*, in: S. Burkhardt, T. Metz, B. Schneidmüller, S. Weinfurter (eds.), *Staufisches Kaisertum im 12. Jahrhundert: Konzepte, Netzwerke, politische Praxis*, Regensburg 2010, pp. 393–395.

⁶ F. Lachenal, H.T. Weise, *Ingelheim am Rhein, 774–1974: Geschichte und Gegenwart*, Ingelheim 1974, p. 63; P. Classen, *Die Geschichte der Königspfalz Ingelheim bis zur Verpfändung an Kurpfalz 1375*, in: J. Autenrieth (ed.), *Ingelheim am Rhein. Forschungen und Studien zur Geschichte Ingelheims*, Stuttgart 1964, p. 138.

the palatium were substantially damaged and the place fell into ruin, as demonstrated by illustrations and descriptions contained in the doctoral thesis of Daniel Schöpflin⁷.

The topography of the palatium in Ingelheim was mainly formed by human impact. There were more intensive changes associated with an extension of the whole area of the residence and minor alterations inside individual buildings. The presented research included only the major transformations within the residence. Natural elements, such as an inclination or exposition, are visible in the reconstructions throughout all periods. A natural slope of the area and sharp boundaries of different buildings of the palace were rendered by the applied method. This issue was described in two manners, namely as a spatial feature and as a qualitative change in time.

The research area is defined as the territory of the palace, currently so-called Saalgebiet (Fig. 3) in the district of the city Lower-Ingelheim [Ger. *Nieder-Ingelheim*]. The time frames are designated within the foundation of the residence and the two first building stages of the residence from the 8th to the 11th centuries.

The main aim of this paper is to reconstruct the historical topography of the palatium in Ingelheim – understood as a historical utility level – using the method of Geographical Information System. The generated models were compared and the differences between particular building phases of the residence were calculated by using map algebra. Subsequently, the size of the transformation area was designated, which was one of the goals of this study. Cross sections of the terrain generated from DTMs were also presented as another way of analysis.

Data sources and the history of archaeological research

The data sources used in this project can be divided into two main groups, spatial and non-spatial data. The first type of data constitutes the basis for the presented research. The second one helped to characterise and distinguish the first set of the data. Archaeological and architectural documentation, cadastral maps



Fig.3. Area of Saalgebiet and the palatium in Ingelheim

and historical plans can be included within the sources of these two data sets (Fig. 4). Two main kinds of the data were essential for the analysis, namely elevation data and the border of the buildings and other areas which were treated as lines of discontinuity during the generation of historical DTMs. The obtained data built a staple part for the reconstruction of the historical topography.

The archaeological documentation that was used to obtain the height data and the lines of discontinuity (barriers) consisted mainly of 'archaeological field drawings', which were made directly during archaeological research and their digital version edited in post/excavation stage. Additionally, reports, descriptions

⁷ D. Schöpflin, *Historia et commentationes academiae electoralis scientiarum et elegantiorum literarum Theodoro – Mannhenii Typis Academicis*, vol. 1, Palatinae 1766, fig. 3, p. 307.

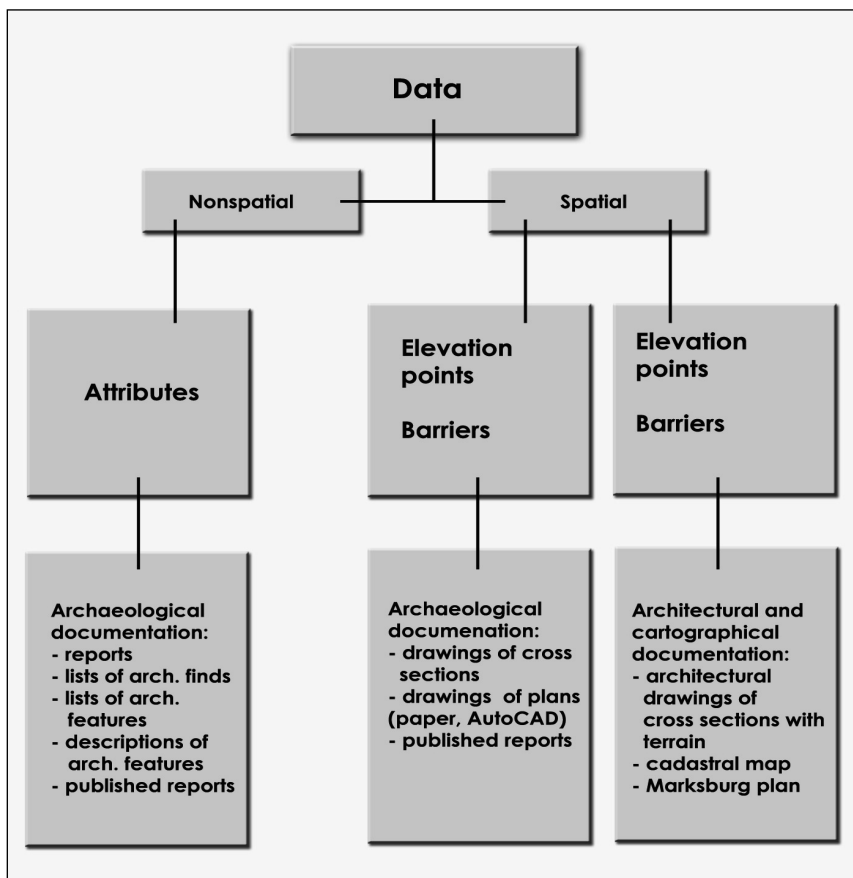


Fig.4. Sources and data used to generate the DTMs

of archaeological features and various publications⁸ about archaeological excavations were used for interpretation of individual archaeological features, their dating and relations between them. The time of documenting the buildings and the height of the utility level played a very important role due to the fact of applying different methods.

Archaeological research in the palatium at Ingelheim was conducted between the years

1909 and 2009. The first regular excavations at this place began over one hundred years ago. They were conducted by an art historian Christian Rauch from 1909 to 1914. Exploring the palace at that time was limited only to the primary area. Although Rauch did not use modern excavation methods, he exposed most of the masonries of this part of the residence. He did not attach too much importance to stratigraphy, which resulted in an erroneous

⁸ H. Grewe, *Geschichte und Neubeginn*, pp. 177–184; H. Grewe, *Die Königspfalz zu Ingelheim am Rhein*, pp. 142–151; H. Grewe, *Die Ausgrabungen in der Königspfalz*, pp. 155–174; H. Grewe, *Die bauliche Entwicklung*, pp. 101–120; H. Grewe, *Visualisierung von Herrschaft in der Architektur*, pp. 383–403; H. Grewe, W. Sage, *Die Königspfalz Ingelheim am Rhein. Auswertungen von Altgrabungen und neue Geländeuntersuchungen*, in: R. Bergmann (ed.), *Mittelalterforschung in Bamberg: Beiträge aus dem Zentrum für Mittelalterstudien*, Bam-

berg 2001, pp. 50–57 (Forschungsforum. Otto-Friedrich-Universität Bamberg, vol. 10); H.J. Jacobi, Chr. Rauch, *Ausgrabungen in der Königspfalz Ingelheim 1909–1914*, Ingelheim 1976; W. Sage, *Die Ausgrabungen in der Pfalz zu Ingelheim am Rhein in den Jahren 1963 und 1965*, „Germania“, 46, 1968, pp. 291–312; W. Sage, *Die Ausgrabungen in der Pfalz zu Ingelheim am Rhein 1960–1970*, „Francia“, 4, 1976/1977, pp. 141–160; U. Wengeroth-Weimann, *Die Grabungen an der Königspfalz*.

interpretation and dating of various buildings of the palace. Rauch included all discovered remains of the building into one – the Carolingian phase⁹.

Evaluation of these first excavations was attempted by an archaeologist Walter Sage in the 1960s. The reason for starting a re-examination was the reconstruction of the nave of the church (Saalkirche). After successful campaigns between the years 1960–1963, research was extended to other important areas of the residence. The applied methods helped to interpret and to date archaeological features and to recognise a stratigraphic sequence for this area. Many theories introduced by Christian Rauch were not confirmed during those excavations¹⁰.

A further review of the previous results was started in 1993. Archaeological excavations have been continued in the whole area of the residence until today within the framework of the research institution called Forschungsstelle Kaiserpfalz Ingelheim. For almost twenty years the main aim of the research has focused on the area of the residence but other areas near the palatium were examined, too. The excavated area up to the year 2009 is about 1785 m², divided into more than 50 single archaeological trenches (Fig. 5).

The quality of the documentation, its accuracy and the methods of its preparation are different, both for various excavation campaigns and for the individual researchers. Some of the results were never published and could not be included in this study. A large amount of archaeological finds and documentation of the research carried out in the years 1909–1914 was lost during the Second World War.

The elevation data and the lines of discontinuity obtained from archaeological documen-

Excavation Sections in Palatium - Ingelheim 1909 - 2009

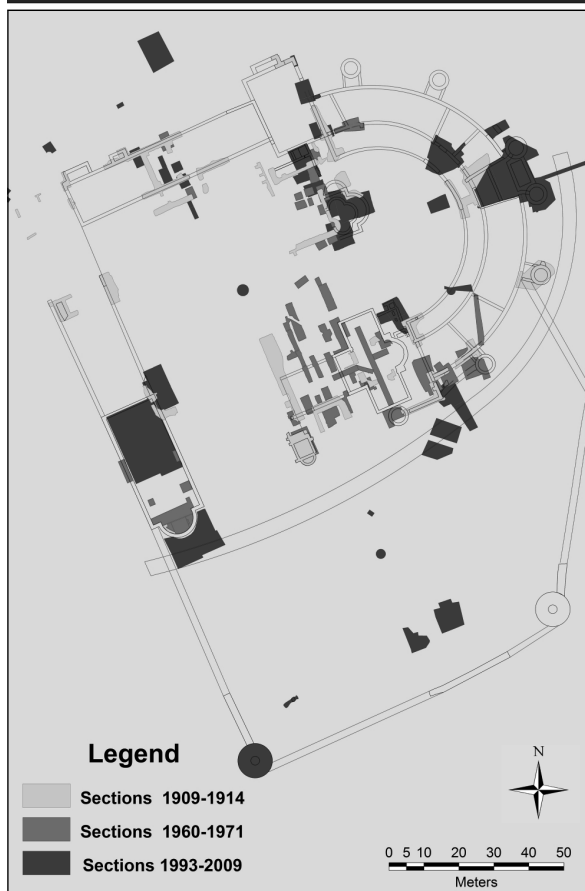


Fig.5. Location of the archaeological trenches in the palatium in Ingelheim between 1909 and 2009

tation were combined in AutoCAD 2008 and imported as dxf file into the GIS environment. Further additional information was added as attributes in ArcGIS 9.2. The exact location of all features was determined by connecting local coordinate systems into one coherent system – the Gauss-Krueger system for the third zone (EPSG 31467).

Some of the information was also obtained from the historical plan Marksburg. The name of this plan (Fig. 6) comes from the place where it was found, i.e. the archives of the Marksburg castle. Presumably, the origin of this source could be connected with the Thirty Years' War and the possible use of the palatium as a de-

⁹ H. Grewe, *Geschichte und Neubeginn*, pp. 178–179; H. Grewe, *Die Ausgrabungen in der Königspfalz*, pp. 157–158; H. Grewe, *Visualisierung von Herrschaft in der Architektur*, pp. 384–385.

¹⁰ H. Grewe, *Geschichte und Neubeginn*, p. 180; H. Grewe, *Die Königspfalz zu Ingelheim am Rhein*, pp. 142–143; H. Grewe, *Die Ausgrabungen in der Königspfalz*, p. 157; W. Sage, *Die Ausgrabungen in der Pfalz zu Ingelheim am Rhein in den Jahren 1963 und 1965*, pp. 291–312; W. Sage, *Die Ausgrabungen in der Pfalz zu Ingelheim am Rhein 1960–1970*, pp. 141–160.

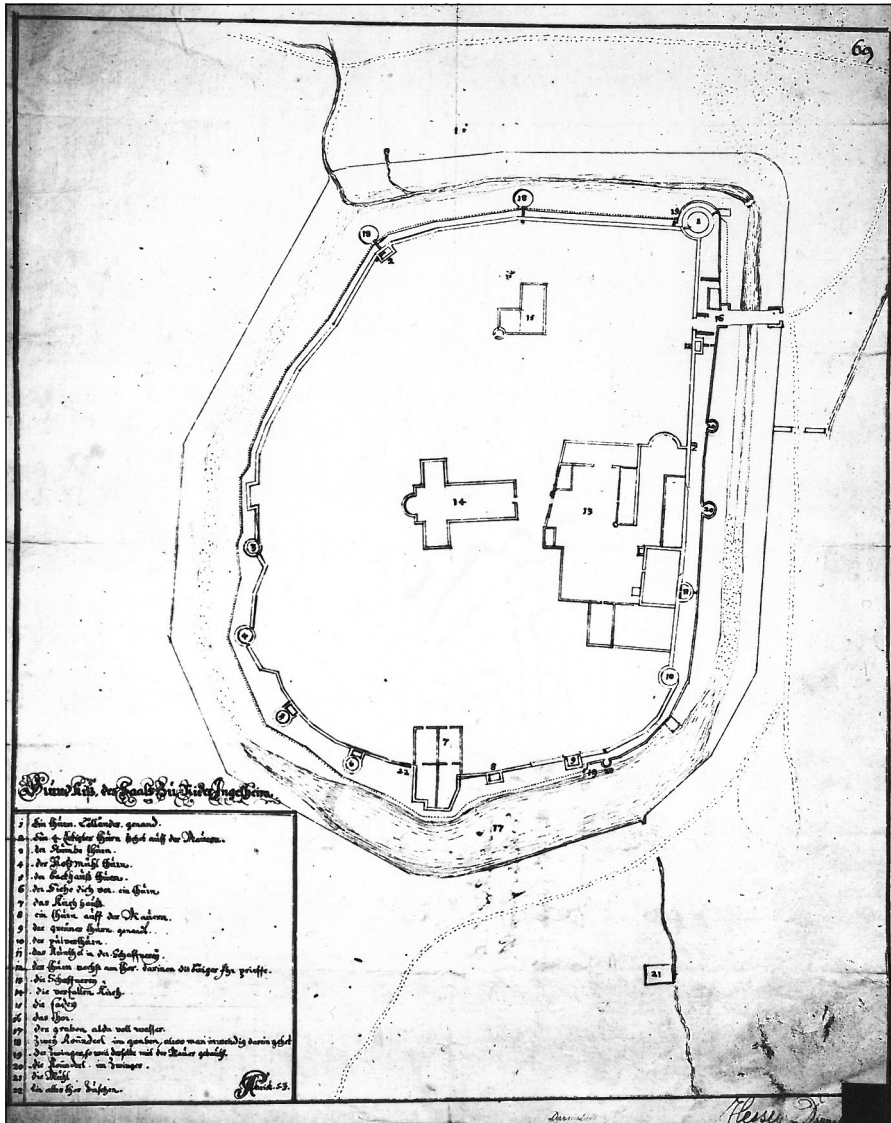


Fig.6. The Historical plan Marksburg

fensive fortress. This plan has a great historical value but it is not a typical cadastral plan which could be compared with modern examples of such sources. In this plan the area of the Saalgebiet was not presented in any cartographic projection. The dimensions of the whole residence and various elements of the urban architecture are not proportionate and consistent with the real constructions, yet they do not deviate from them heavily. The map is oriented

to the south. The lack of scale and a typical cartographic key is also noticeable, although it is a descriptive one. Important buildings are numbered and briefly characterised by the plan's developer. The map does not provide information about the year of origin and references to the author are illegible. The plan was preserved only in the form of low-quality photocopies (12.63x15.60cm) but for the purpose of this study the digital version (jpg) with a resolution

of 300 dpi was used. Unfortunately, there is no information about the original dimensions of this historical plan.

Methodology

Almost all operations on the data were conducted in ArcGIS 9. 2. Only the initial stage of data collection was executed in AutoCAD 2008, which resulted from over fifteen years of digitalisation of archaeological field drawings with this software. In the first stage of the project all of the elevation points and the borders of the buildings were extracted from all of the sources. Additionally, for the reconstruction of moat boundaries the Marksburg plan was georeferenced. After initial controlling of the data quality and trial interpolations the main method for the final generation of DTMs was chosen. In the closing phase of this research new interpolated DTMs were compared and evaluated.

Operation on the data – elevation points

The collected data used to generate the Historical Digital Terrain Models were subjected to double verification. This was carried out separately since the points-data express the elevation in each location and the lines of discontinuity (barriers), thereby two data features were created. The data were linked over editing of the database to a specific building phase – 1st to 3rd ones. Determination of the location of points was based on the location of the unique excavation trench and the unique archaeological feature. An important element in understanding and determination of the exact height was the type of archaeological feature related to a particular utility level. The following objects were distinguished and interpreted

as an approximate utility level: boundaries between geological layers and those of anthropogenic origin, stone settings and screeds used to harden the floor, the upper limit of the foundations, the lower limit of the burnt layers, stairs, doorsteps etc.

During the next review a group of the points was determined to a representative set of data and reduced by those with significantly different values. This selection was carried out in two phases. The first phase was limited to distinguishing a group of points for a particular building phase. Each group was verified by comparing values of the neighbouring points. Elimination of a great number of points was made using the classification and exclusion of selected extreme values. A specific set of the points assigned by selecting an individual historical period was verified by comparing their values including the lines of discontinuity. Points with different extreme values were removed from the set, unless their values were connected with an intentional human activity. The next verification was performed by using an interpolated surface to specify areas with significant disparate values of pixels.

Operation on the data – discontinuity lines

Discontinuity lines (barriers) define changes in the terrain conditioned mainly by human activity. This includes boundaries of archaeological objects, such as a moat or stone buildings of the palace. The data interpreted as barriers were obtained from both excavations and from a unique historical cartographical source (Marksburg plan). Some of them were completed by adopting a reconstruction of the residence. These barriers were used to generate the terrain models of the site for the medieval palace as well.

Tab. 1. Number of points in the preliminary and the representative set

DTM	Number of points in the preliminary set	Number of points in the representative set
1 st phase – 8 th century	247	225
2 nd phase – 8 th / 9 th centuries	338	206
3 rd phase – 10 th and 11 th centuries	283	204

All lines of discontinuity which were reconstructed on the basis of the above-mentioned sources were introduced to the preliminary set of data. They were digitised as a separate class

riers inside the aula regia and its atrium were removed. The division between this hall and its apse was left because of differences in the elevation of these two parts of the building.

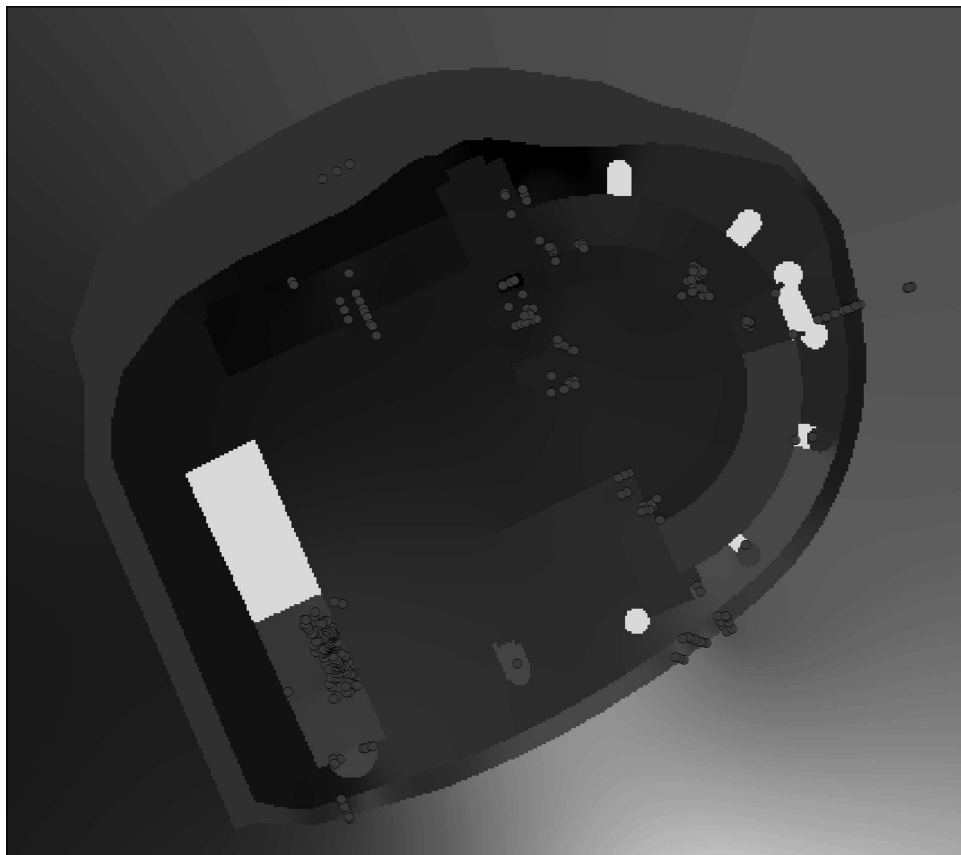


Fig.7. Results of the preliminary interpolation before generalisation of the barriers

of objects (lines) with the type of archaeological feature and building phase of the residence as attributes.

Not all of the reconstructed discontinuity lines could be used to generate terrain models. Some of them proved to be too accurate in relation to the number of the elevation points which were collected for analyses (Fig. 7). Some lines had to be removed from the set to generate DTMs. This was done mostly in the case of small spaces belonging to the residence, such as towers and a single room within a larger building. For example, the bar-

The rooms in the northern part of the palace and also in the exedra were generalised due to an insufficient amount of information about the elevation of the utility level. A preliminary generalisation of the line of discontinuity was conducted by using interpolation methods. Barriers which greatly influenced formation of gaps in the model were removed from the database. After the first interpolation all of the collected lines were divided into building phases of the palatium 1st to 3rd and combined in subsequent sets.

Georeferencing and assessment
of the cartometric accuracy
of a historical cartographic source

The georeferencing procedure of the Marksburg plan was also conducted in ArcGIS 9. 2. The control points for georeferencing were obtained from both the measurements of the remains of the palace buildings and from the archaeological documentation. The total number of the control points used to the georeferencing amounts to 18 (stable and unstable points). There are mainly characteristic points such as corners of the buildings or wells.

The values of the point coordinates correspond to the Gauss-Krueger map projection and are read from the cadastral map of Ingelheim and the vectorised reconstruction of the palatium. After entering the plan as a JPEG file to ArcGIS, the individual control points were marked on the plan and combined with the corresponding points on the cadastral map and the reconstruction of the residence. This process was carried out using various methods ranging from the first polynomial to the spline, which gave the best results. Although this method affects the local accuracy of the source, the image after georeference seems to better fit into the reconstruction of the palace than the result of the method of the first to the third polynomials. This is probably due to the fact that the control points are regularly distributed in all areas with building.

The accuracy analyses of the historical Marksburg plan were carried out by applying the following methods: scale analysis, distance analysis, circle method and distortion grid. For measurements of real values and comparison with the historical cartographical source, a modern cadastral plan of Ingelheim from 2008 was used. Subsequently, archaeological data such as vector drawings (CAD) and survey measurements of some visible relicts of the medieval palatium were added to the procedure.

The selection of stable points was one of the most crucial issues of the analysis. During the recent centuries the research area has been changed due to urban development, therefore

the selection of these points required a high precision and exactness. In particular, many of the stable points applied to the analysis were no more visible as part of architecture, but



Fig.8. Total station surveying during the excavation – stable point number 8

their position was assessed and measured during archaeological excavations (Fig. 8).

They had to be identified both in the historical plan and in the modern reference plan from 2008. Independent sets of the stable points for the plan Marksburg and for the modern plan were selected. The total number of the selected stable points amounts to 38 points (Fig. 9).

Further analysis was based on the assumption that the points placed in the modern plan were accurate. Contrary to that, the points presented in the historical plan were presumed as inaccurate. Subsequently, a major impact on the result of accuracy analysis was exerted by

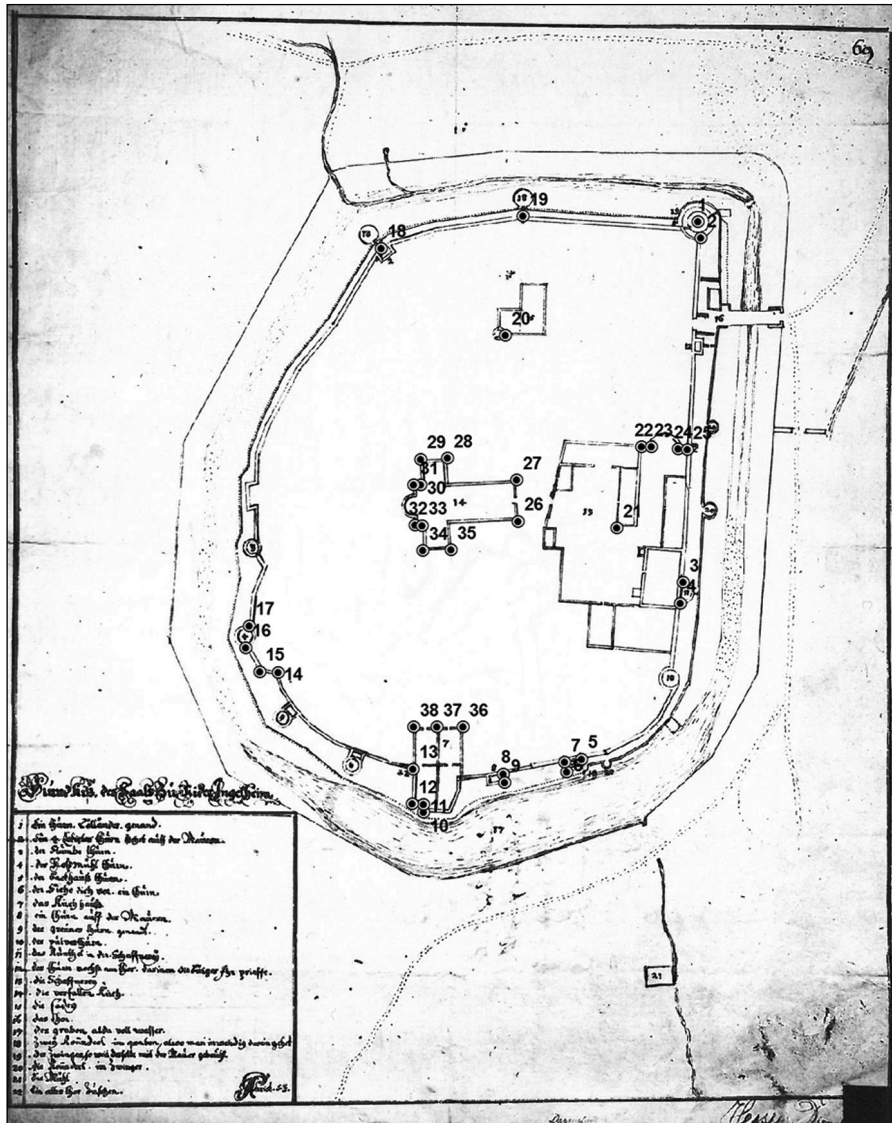


Fig.9. Distributions of the stable points on the historical plan Marksburg

the number and spatial distribution of the stable points. However, these points were used to calculate the average local scales and to generate the distortion grid.

The scale of the historical plan was calculated as an arithmetic mean based on the local scales that were measured as a distance between the identified stable points. During the procedure 703 of measured distance (local scales) between 38 points were obtained. On this ba-

sis the arithmetic mean value of the local scale of the Marksburg plan was computed. For this purpose a script *Spider Diagram Tool* for ArcGIS was implemented (Fig. 10).

The outcome of this analysis was the approximate scale 1: 2403. The extreme range of the computed scale oscillated between 1: 1697 (in the map section between the stable points 30–31) and 1: 3319 (in the map section between the stable points 6–9) (Fig. 11).

The distance analysis was based on the absolute values of Gaussian mean error which was calculated for each point as a sum of the distances between all stable points, both for the modern

plan and for the historical plan. To obtain the best results the sections (distances) between the stable points had to be as long as possible and have various directions¹¹. The distance analysis of the Marksburg plan was carried out based on 1406 precisely measured distances between each stable point, expressed in meters. These values are summed and assigned to the each stable point as absolute distance errors from the given point to the rest 37 points. The largest error occurred in stable point 18 and it amounted to 279.24 m. The smallest error occurred in stable point 24 and its value was 77.95 m. The absolute Gaussian mean error calculated for the historical Marksburg plan is 135.5 m. The final results of calculations were presented in the table and as graph (Fig. 12).

Except the tabular (table) form the results of this calculation were also presented using a graphical method. In this case, the circle method to visualize the outcomes was applied. The first researcher to implement this method in 1986 was P.G.M. Mekenkamp. The theoretical basis of this method was developed in the diploma thesis in 1996 by Ch. Steiner¹². The size of the circle (diameter) around each stable point was proportional to the sum

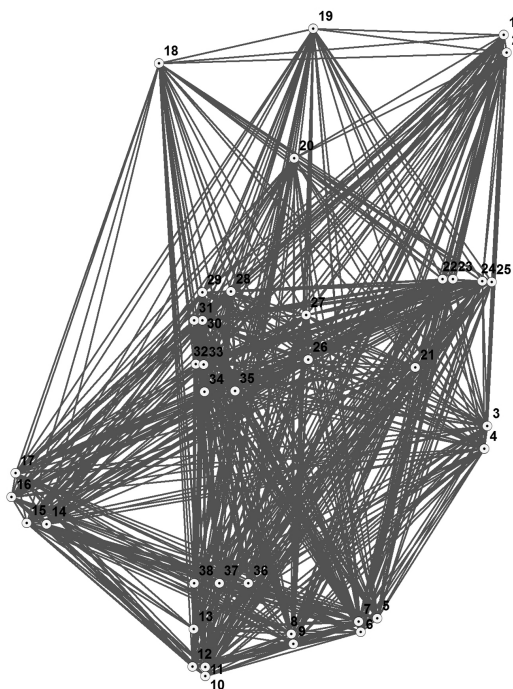


Fig.10. Spider Diagram for the historical plan Marksburg

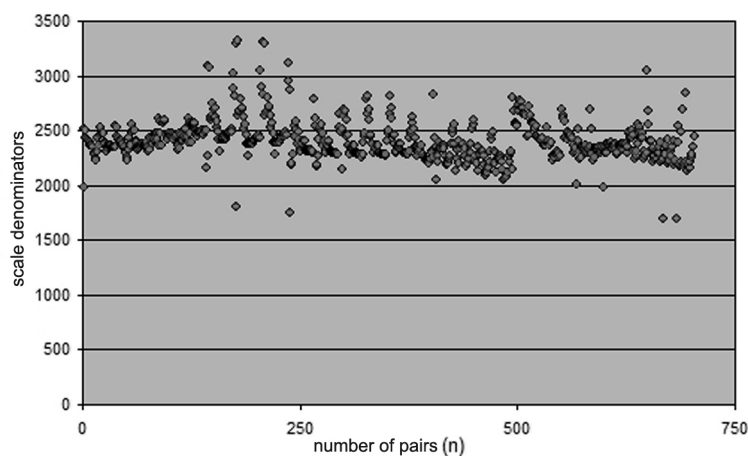


Fig.11. Range of the local scales

¹¹ J. Niederöst, *Das Relief der Urschweiz von Franz Ludwig Pflyffer (1716-1802): 3D-Rekonstruktion, Analyse und Interpretation*, Zürich 2005, p. 58 (PhD Thesis ETH, nr 16077).

¹² G. Forstner, M. Oehli, *Graphische Darstellung der Untersuchungsergebnisse alter Karten und die Entwicklung der Verzerrungsgitter*, „Cartographica Helvetica“, 17, 1998, pp. 35–43.

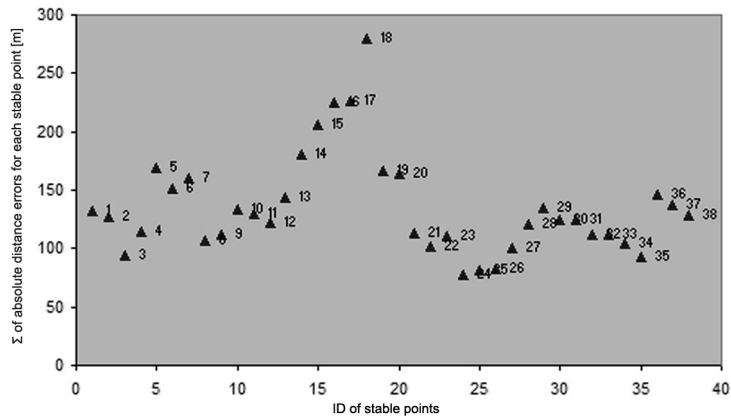


Fig. 12. Range of the sum of absolute distance errors for each stable point [m]

of inaccuracy from the given point to the rest of 37 points. Essentially, the smaller circle (diameter) around a stable point, the more accurate position of a historical map is¹³. The graphical presentation of the results of the distance analysis shows the absolute calculated distance error for a particular stable point (Fig. 13).

A distortion grid is a widely used graphical method to analyse the accuracy of a cartographical source. It is one of the oldest methods used for graphical representation of uncertainty on historical cartographical sources. For the first time this method was presented by Hermann Wagner in 1895–1896¹⁴.

The principle of this method is to create a regular grid of lines in a geographical or Cartesian coordinate system based on the contemporary (modern) map and its transformation by using identical reference points (e.g. stable points) to the projection of an analysed historical map¹⁵. “Its construction consists in a transfer of the grid from the modern map to the historical cartographical source with changes of the course of the line according to the location of individual components. [...] The end result is a net whose meshes are no longer rectangles but become irregular forms. This method can

also be used to examine the plans of cities, including those which are devoid of coordinates. For this purpose a grid of straight lines should be created on the modern cadastral map and transferred to a historical plan based on details of the topography of the city”¹⁶.

Creating the distortion grid and its size are not explicitly referred to in the literature. A distortion grid should cover all of the stable points on the modern and historical map. The size and density of the mesh (grid) should be included in each map to capture any possible local anomalies¹⁷. For example, the distortion grid used by Kamil Nieścioruk for a historical plan of the city of Lublin had a mesh size of 200 x 200 m¹⁸. The final grid size created for the Marksburg plan had a mesh with the dimensions of 15 x 15 meters (Fig. 14). This grid was transformed using the spline method, which is a true rubber sheeting method. It is the optimal method for the local accuracy but not for the global correctness¹⁹. This transfor-

¹³ D. Nell, *Methoden der Genauigkeitsanalyse historischer Karten*, Wien 2009, p. 28 (Diploma Thesis, Universität Wien).

¹⁴ G. Forstner, M. Oehrl, *Graphische Darstellung*, p. 37.

¹⁵ D. Nell, *Methoden der Genauigkeitsanalyse*, p. 22.

¹⁶ K. Nieścioruk, *Metodyczne aspekty kartograficznej analizy i oceny dawnych planów miast na przykładzie planu Lublina z 1716 roku C. d’Orkena*, Lublin 2006, pp. 40–41 (Dissertation, UMCS Lublin).

¹⁷ D. Beineke, *Verfahren zur Genauigkeitsanalyse für Altkarten*, Neubiberg 2001, p. 113 (Dissertation, Schriftenreihe des Studiengang Geodäsie und Geoinformation der Universität der Bundeswehr München, vol. 71).

¹⁸ K. Nieścioruk, *Metodyczne aspekty*, p. 112.

¹⁹ ArcGIS 9.2 Desktop Help. *Georeferencing a raster dataset*, 2008 (On-line: http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=Georeferencing_a_raster_dataset, accessed: November 2013).

mation is very common if the precise location of stable points is required.

The results of the analysis using the distortion grid show that the most distorted sectors of the Marksburg plan are located in the southern and eastern part of the historical plan. In other parts of the residence the distribution of the mesh is fairly regular. The distorted grids were formed as a result of local scales variability and clustered distributions of the stable points.

To sum up, one can point out that the content of the Marksburg plan is highly generalized (thematic map), and shows only selective elements of the historical urban space, e.g. ecclesiastical buildings (church), fortifications of this area, the moat and the mill. This could have an adverse effect on an insufficient number of stable points and lead to unequally distribution of stable points on a historical map. Spatial distribution of 38 stable points was analysed by using of the Average Nearest

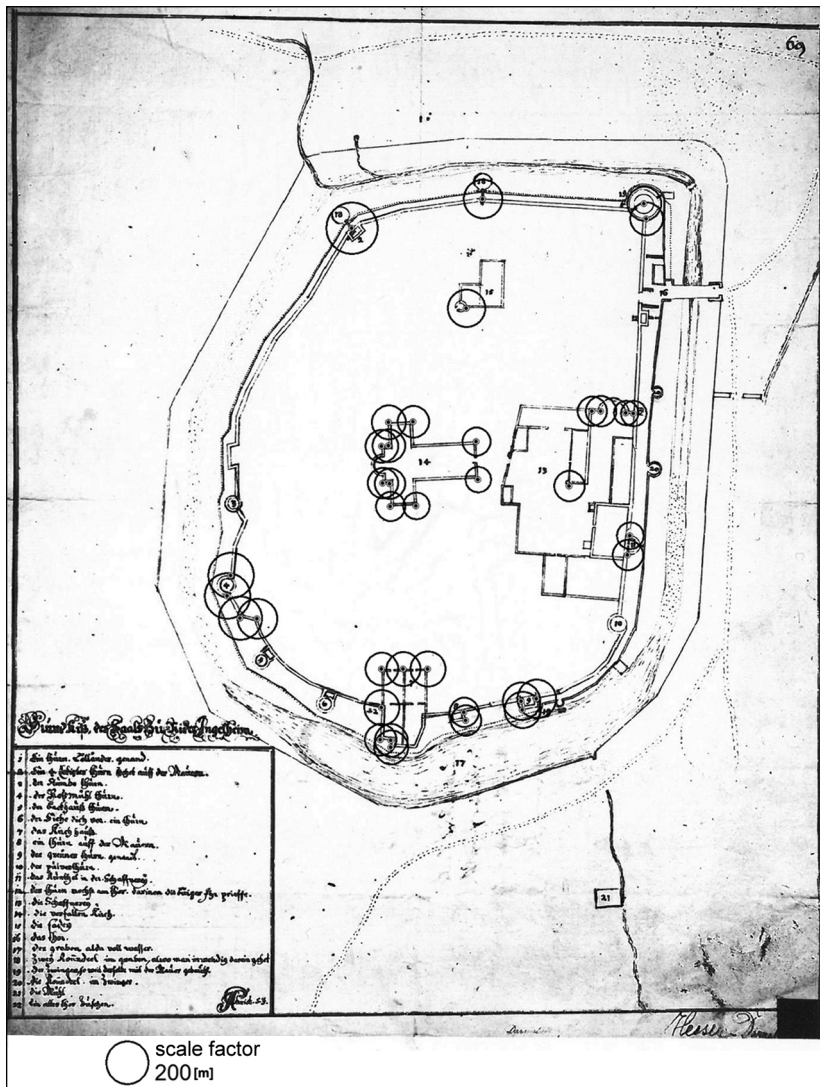


Fig.13. Circle method showing the sum of absolute distance errors for each stable point [m]

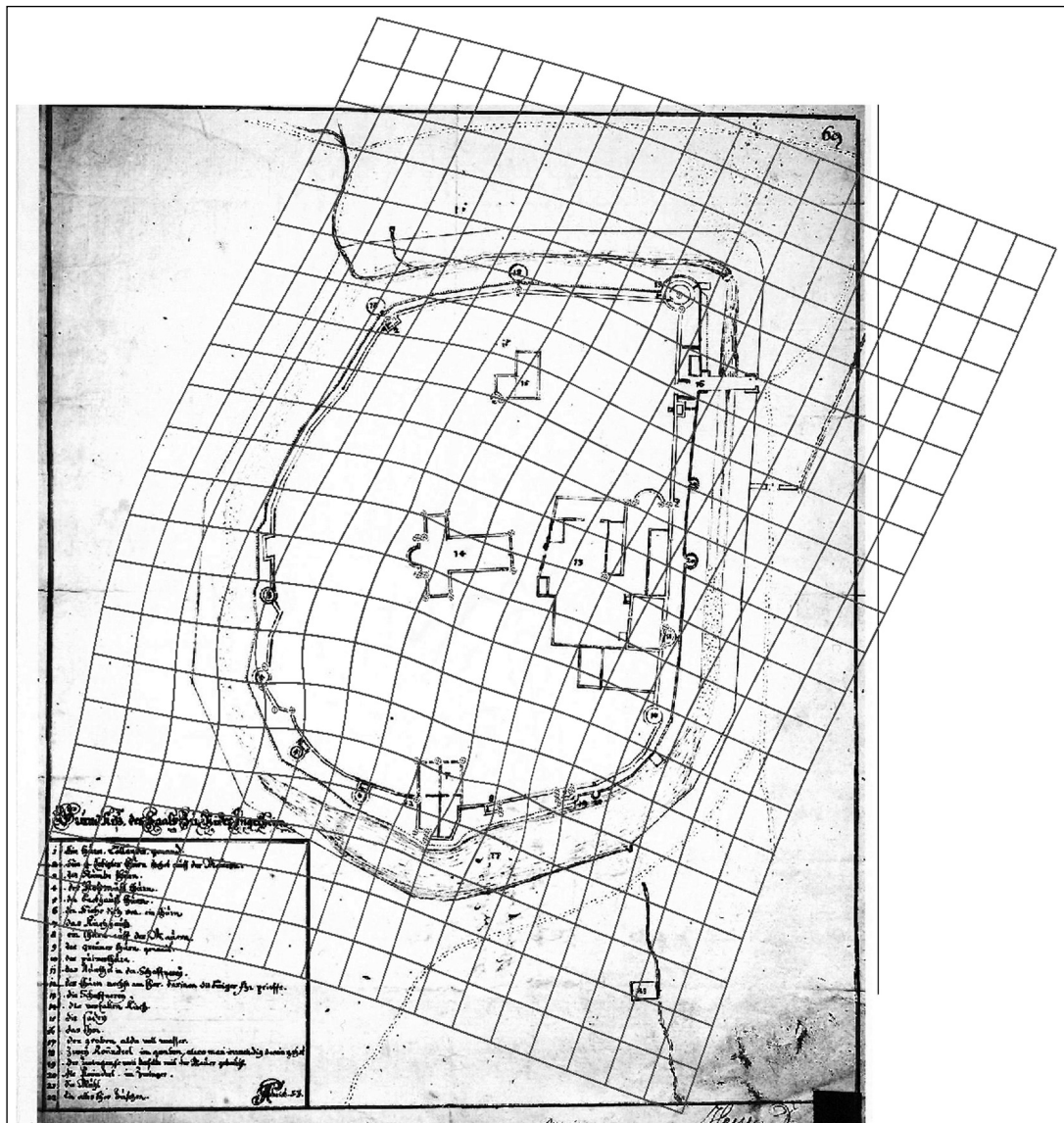


Fig.14. Distortion grid for the historical plan Marksburg

Neighbor (Spatial Statistics) in ArcGIS. The results show that the points have a cluster distribution which could have an adverse influence on the accuracy of the analyses and on georeferencing of the historical plan Marksburg (Fig. 15).

The conducted cartometric analysis of plan Marksburg shows that the planimetric accuracy of this source is generally limited; how-

ever, its historical importance is invaluable. In conclusion, there is a variety of local scales occurring in the plan. Mesh deformation in the distortion grid also corresponds with the variability in the local scale. There is also some visible mesh distortion in areas of the stable points, in which the largest error of the sum of absolute distance errors for particular points appears.

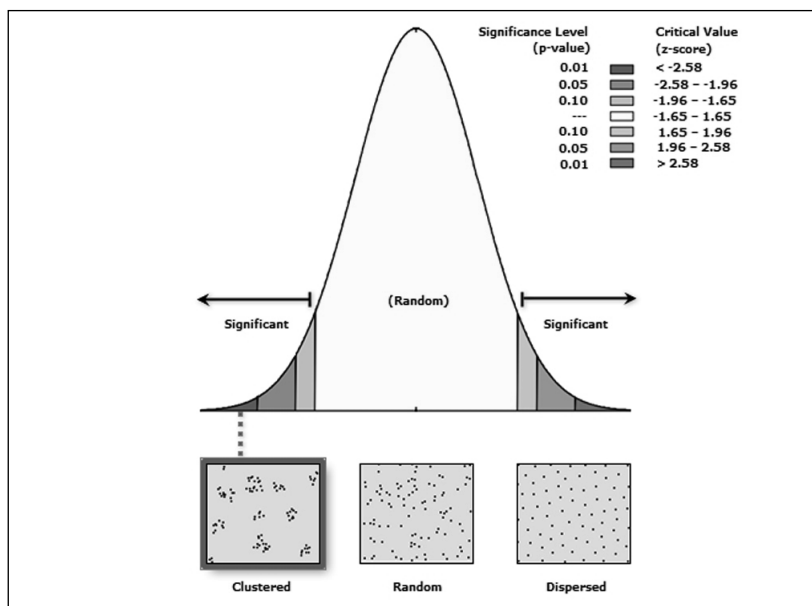


Fig.15. Results of the Average Nearest Neighbor analysis computed in ArcGIS

Interpolation

Spatial interpolation is one of the most important calculation procedures in geoinformation systems. It is a kind of prediction of a value at a point for which we do not have any measurement data. Interpolation is based on Tobler's First Law about spatial autocorrelation, which implies the existence of a weakening mutual influence of characteristics of the neighbouring objects which change smoothly or gradually with increasing distance²⁰.

There are many interpolation methods which can be divided into two main groups listed here with examples of the specific method:

- The stochastic interpolation method: kriging
- Deterministic interpolation methods: inverse distance weighting, spline

Stochastic methods are based on the theory of probability. The interpolated surface is treated as a derivative. This process allows calculation of the level of statistical significance and the statistical uncertainty of forecast values. The deterministic methods model the surface in a way specified by mathematical functions.

Designated values are calculated on the basis of sample points in the neighbourhood of a particular pixel²¹.

Among the deterministic methods global and local interpolations can be distinguished. The global methods are used to define relationships between certain values for an entire test area, e.g. global trends. Opposite to that, the local methods generate values for a smaller terrain. Changing of a particular value of a unique point in the first case affects the overall result, the second process changes pixels located in the vicinity of this point²².

In the presented research the following interpolation methods were applied: inverse-

²⁰ P.A. Longley et al., *GIS. Teoria i praktyka*, Warszawa 2006, pp. 67, 340.

²¹ *ArcGIS 9.2 Desktop Help. An overview of the interpolation tools*, 2008 (On-line: http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?id=4996&pid=4995&topicname=An_overview_of_the_interpolation_tools, accessed: March 2010); M. Kappas, *Geographische Informationssysteme*, Braunschweig 2001, p. 188.

²² *ArcGIS Geostatistical Analyst: Statistical Tools for Data Exploration, Modeling and Advance Surface Generation*, 2001 (On-line at: <http://www.esri.com/library/whitepapers/pdfs/geostat.pdf>, accessed: January 2009); M. Kappas, *Geographische Informationssysteme*, pp. 188-189.

distance weighting and spline. This choice was dictated by the possibility of including the discontinuity lines.

Inverse distance weighting is one of the most commonly used interpolation methods and a direct implementation of Tobler's First Law. The value of the variable at the point of interpolation is determined as the average weight of the surrounding data. The algorithm used in IDW calculates a variable on the basis of measurement data while maintaining their values. It can give incorrect results in a place of rapid changes of the surface and in an area not covered by measurements²³.

An interpolated surface using the spline method is smoother and has the same data values at their locations. In principle, this method is suitable for the reconstruction of undifferentiated surfaces. In ArcGIS, two types of this process could be chosen, namely regularised [org. regularized] and tension spline. The second one allows one to generate more irregular terrain while maintaining values of sample points²⁴.

In certain interpolation processes it is possible to take into account the discontinuity lines, which could lead to abrupt changes in the raster image. In ArcGIS 9.2 the barriers could be included only to the two above-mentioned methods: inverse distance weighting and spline. This option is used to define certain discontinuities of the surface which were included in the database as vector data – lines without any height values²⁵.

The created models are treated as Digital Terrain Models; they include the barriers and information about elevation, all critical points,

minima, and culminations of the terrain formed by human activity. All interpolated DTMs represent 2.5 D surfaces; they describe neither the depth nor the third dimension of objects.

The Digital Terrain Models were interpolated for the following phases of the building development in the research area:

1. The moment of preparation of the terrain for the building of the palatium – 8th century
2. The Carolingian phase – 8th/9th centuries
3. The Ottonian and the Salian phase – 10th and 11th centuries

The default parameters were used in a preliminary interpolation with the inverse distance weighting method. These include the number of points, which indicates the number of samples to be included to the interpolation of a pixel²⁶, the power and the radius. The size of cells was determined after comparing the two parameters, namely the largest range of all points and the shortest distance between them. In the first case this distance was about 250 m, while in the second it was about 7 cm. The value of 250 m was divided by the number 250 to receive the value of the resulting cells²⁷. Due to the specific excavation method the samples have a cluster character. In view of the irregular spatial distribution and the difference between two previously mentioned values, the average dimension of the cells amounts to 0.5 x 0.5 m.

Additionally, the smoothing factor of 0.5 was introduced into the spline method. The higher the number, the smoother the interpolated surface is. The smoothing should occur in areas bounded by lines of discontinuity, but this should not cause a large change in the generated models.

A subsequent aspect that had a large influence on the final choice of the interpolation method was an image of the generated surface with the lines of discontinuity. The first sample

²³ M. J. De Smith, M. F. Goodchild, P. A. Longley, *Geospatial Analysis – a comprehensive guide*, 3rd edition, 2006–2009 (On-line: <http://www.spatialanalysisonline.com/output/>, accessed: November 2009); P.A. Longley et al., *GIS. Teoria i praktyka*, pp. 341–342.

²⁴ *ArcGIS 9.2 Desktop Help. Applying a spline interpolation*, 2007 (On-line: http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?id=4793&pid=4790&topicname=Applying_a_spline_interpolation, accessed: January 2010); *ArcGIS 9.2 Desktop Help. How spline works*, 2008 (On-line: <http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=How%20Spline%20works>, accessed: January 2010).

²⁵ *ArcGIS 9.2 Desktop Help. IDW (3D Analyst)*, 2007 (On-line: [http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?id=999&pid=998&topicname=IDW_\(3D_Analyst\)](http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?id=999&pid=998&topicname=IDW_(3D_Analyst)), accessed: January 2010).

²⁶ *ArcGIS 9.2 Desktop Help. Applying a spline interpolation; ArcGIS 9.2 Desktop Help. An overview of the interpolation tools*.

²⁷ *ArcGIS 9.2 Desktop Help. Spline*, 2008 (On-line: <http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?id=5002&pid=4995&topicname=Spline>, accessed: January 2010).

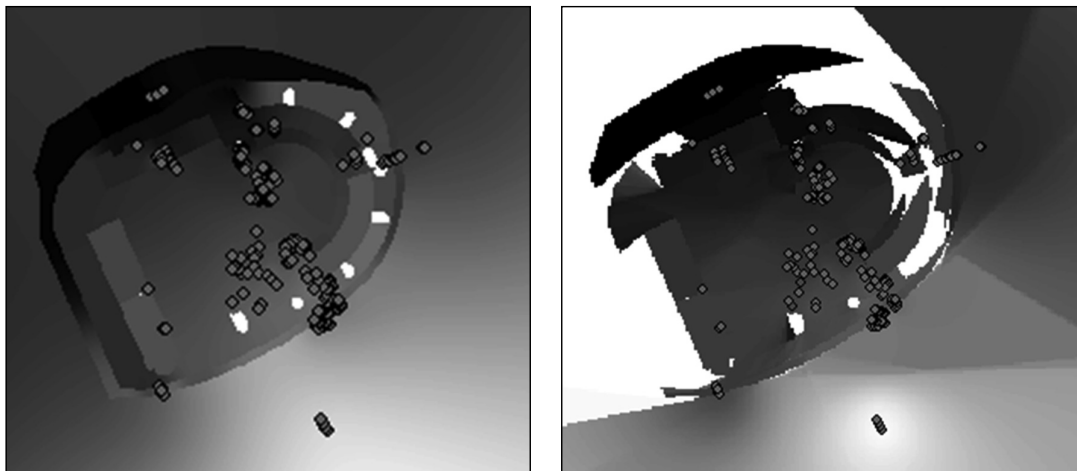


Fig. 16, 17. First trial interpolation using the spline and the IDW with the elevation data

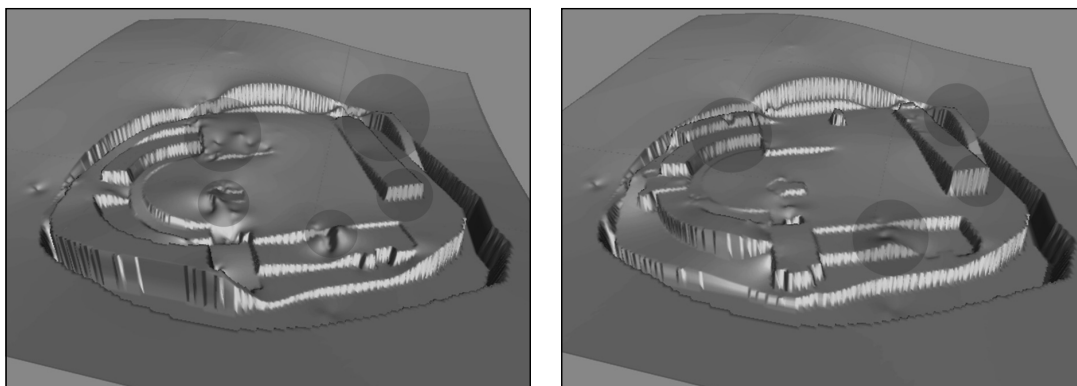


Fig. 18, 19. DTM of the palatium (1st and 2nd phase) after preliminary evaluation

interpolations showed that some of the lines had to be eliminated from further analyses. The generated image contained too many pixels with a NoData value opposite to the aim of the research to create a continuous surface. The main influence on the formation of NoData pixels had a lack of the elevation data for specific areas. The following image presents an example of the surface interpolated using the spline and the IDW method in the preliminary phase of the research (Fig. 16, 17).

As can be seen in the above-placed illustrations, the spline method gave better results of the interpolated image. The second method (IDW) was very time-consuming; one trial in-

terpolation took about 60 minutes. Despite the removal of a large number of barriers, the attempt to create a continuous surface with the IDW method was unsuccessful. These first results of the interpolated surface had an influence on the final choice of the method. The spline method was used for further interpolations.

The results of the initial interpolation with the spline were evaluated by visual-subjective-method in the next stage of the analyses²⁸.

²⁸ T. Podobnikar, Z. Stancic, K. Oštir, *Data integration for DTM production*, 2000 (On-line: http://iaps.zrc-sazu.si/files/File/Publikacije/Data_integration_for_DTM_production_ISPRS.pdf, accessed: October 2009).

Models performed for the first three building phases were visualised in ArcScene and checked for their correctness. The following aspects of the models were taken into account in the review: an elevation of the surface against the neighbouring area, an architectural compatibility of neighbouring areas and a disorder in a given area.

The following figures (Fig. 18, 19) represent two models discussed after the evaluation and the marked areas intended for possible further analyses. To improve the models some minor changes in the set of representative points had to be inserted to the further process. Finally, proper interpolations with the representative set of points were executed. This process was repeated for each building phase of the palatium.

Comparative analysis

The analysis of changes of the land formation and the different elevations between the unique building periods of the palatium were carried out in two ways, using map algebra and as a comparison of cross sections, parallel and perpendicular to the natural slope of the terrain of the residence.

The ModelBuilder, available in ArcGIS 9.2, was used for this analysis. It allows one to create a conduct scheme, to optimise and automate the entire process. Figure 20 shows an example of this scheme, which was also used to calculate the differences of the surface between the first and second building phases.

From the height values of the second surface the elevation values of the first surface were deducted, then the results were reclassified as a value of 1 and 2. Reclassification was used to designate the real boundary of changes. All values with a minus and value of up to 10 cm were used as an unchanged area by analysing the 1st to 3rd phases. The result is the number of pixels for each set which was converted to square metres.

The cross sections were also used for an analysis of the differences between the various building phases of the palatium. They were created by the tool – 3D Analyst in ArcGIS 9.2. For all three phases the cross sections intersect the main axes of the primary area of the residence. The cross sections are designated approximately on the lines north-south and east-west. Their location is also related to the slope

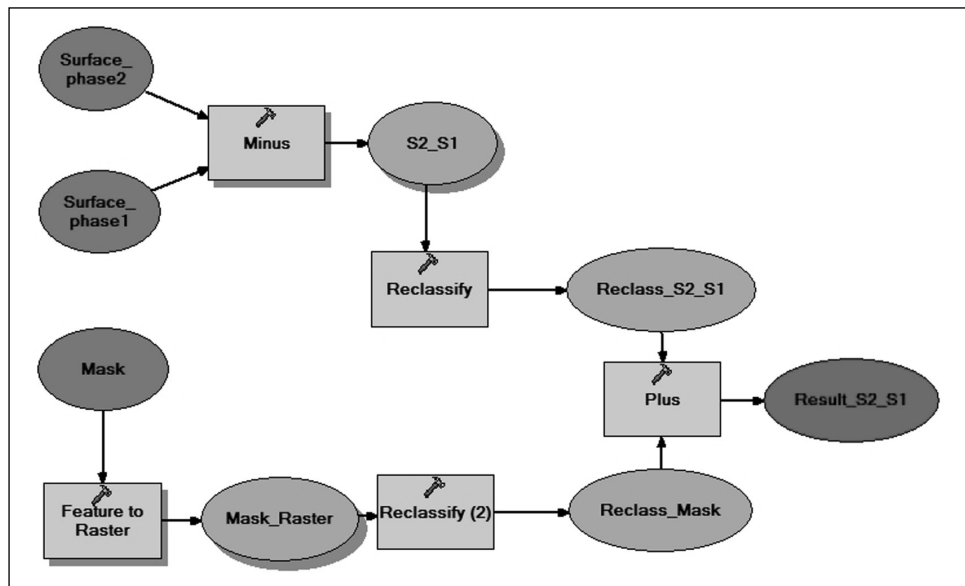


Fig. 20. Diagram of the proceedings during the comparative analysis of the surface for various building phase of the palatium, an example of 1st and 2nd phases

of the terrain. The cross sections on the south-north line are parallel to the slope; the others on the east-west line are perpendicular to it.

Results

In all generated models (Fig. 21–26) three main areas of disturbance or their deficiency were marked. In the southern part of the area it was impossible to generate the correct elevation and form of the moat in any of these models. On the top of the figure in the marked circle some convexities were created in the moat area, which is incompatible with its reconstruction and function. This indicates the archaeological features and remains of a moat which were found on the site south of the aula regia situated close to the described area. This incorrect result is due to the interpolation procedure and the course of the discontinuity lines, which form almost the right angle in this place.

Some anomalies in the generated images were also found in the northern part of the palace. Elevation of the terrain on the eastern part of the northern building appears to be incorrect as well. The high data was collected only for this area, which clearly showed that the decline in the northern and eastern directions was more gradual. This could be interpreted as an anomaly of the model. The other parts of the area are only partially inaccurate; in this case the boundary of the moat appears too rapid.

Certain small disruptions of the raster in unique areas of the palatium occur in the first model. They arise as a result of height differences of specific neighbouring points. These errors could be reduced by a partial elimination of the data without affecting the loss of information.

There is a fairly visible increase of the terrain in all three models in the southern part of the palatium. This was also confirmed during the archaeological excavations. This illustrates quite rapid changes of the slope in the north-eastern direction, which was probably a bit smoother than the differences shown in the models. These results could be interpreted as interpolation errors.

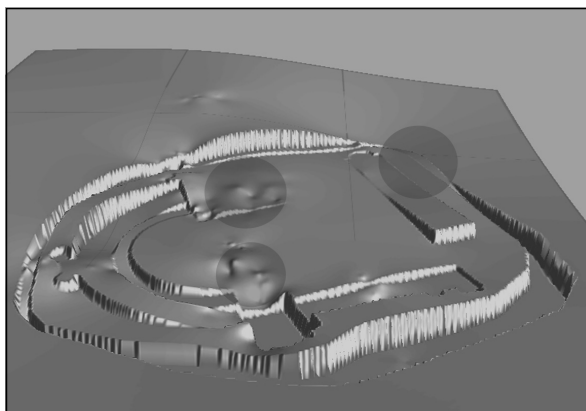


Fig. 21. Digital Terrain Model of the palatium before its building (1st phase), the model is oriented in the southern direction

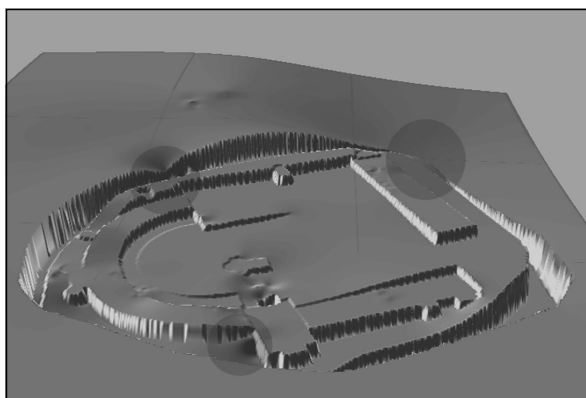


Fig. 22. Digital Terrain Model of the palatium (2nd phase), the model is oriented in the southern direction

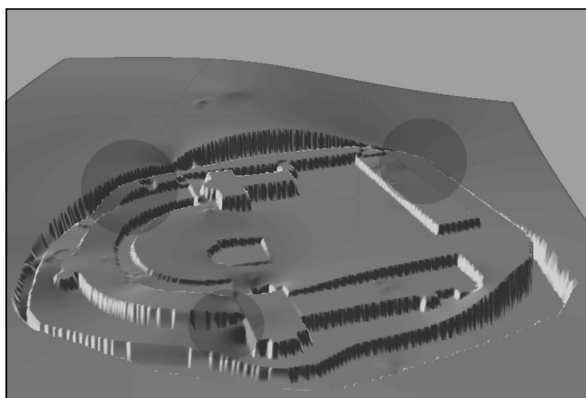


Fig. 23. Digital Terrain Model of the palatium (3rd phase), the model is oriented in the southern direction

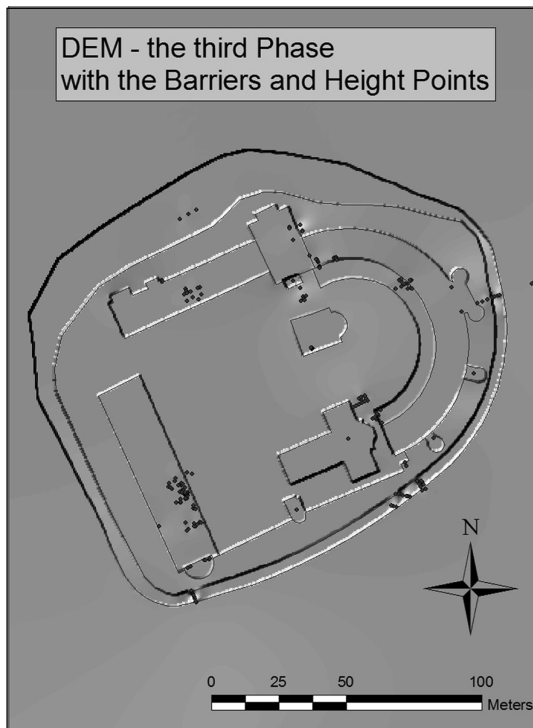
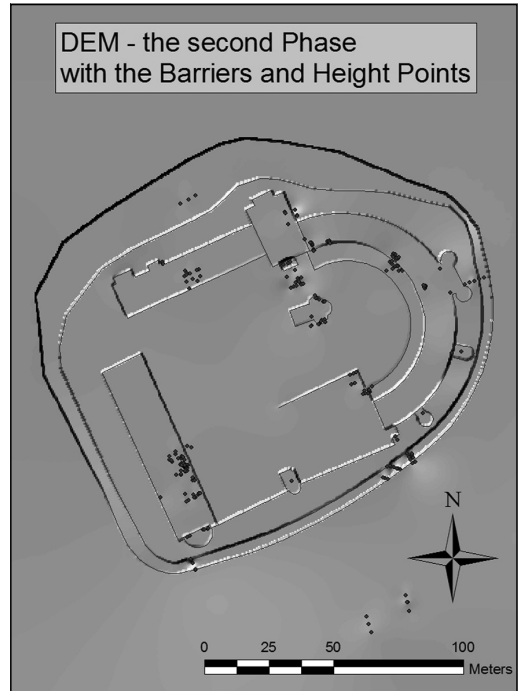
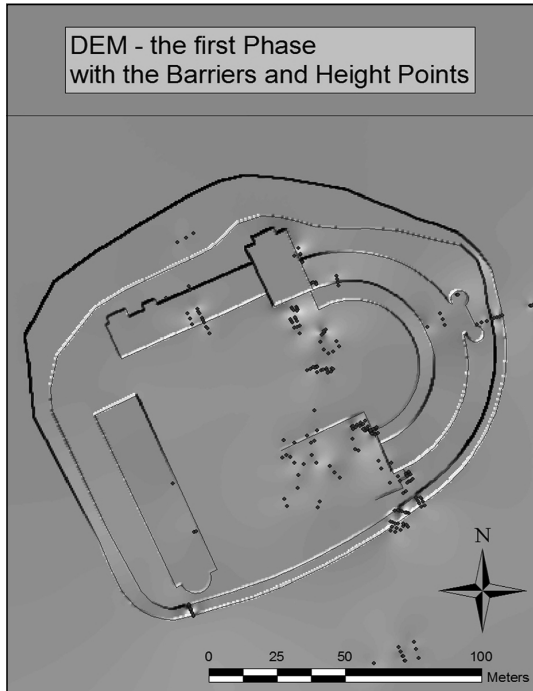


Fig. 24–26. Digital Terrain Model with the elevation data and the barriers for the first to third building phase of the palatium

Comparative analysis of DTMs based on calculation of elevation differences between images and collation of identical cross sections of the terrain. As already mentioned, differences of each model were designated by the map algebra. The exact scheme of this process is shown in Figure 20. The analysed areas were reduced to the outside borders of the moat.

The following models were compared:

- Models of the 1st and 2nd building phases for the main palace area
- Models of the 2nd and 3rd building phases for the main palace area

The first analysis shows that a sizable area of the palace was changed (Fig. 27, Tab. 2). These results correspond with the transition from the 1st phase to the 2nd phase and it refers to the building process of the residence. The differences were noticed primarily for the buildings and the central part of the palatium. The area of the moat and between this construction and the internal part of the palace was almost unchanged. The terrain designated on the map as the differences within the moat is related to the errors of the interpolation.

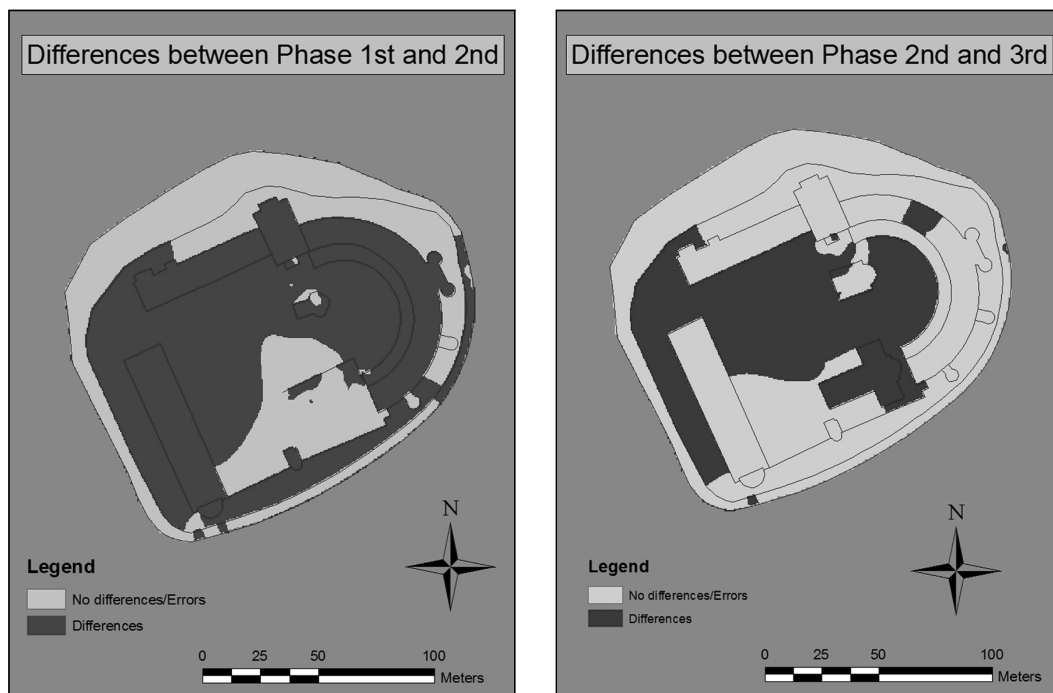


Fig. 27, 28. Differences between the 1st and 2nd, 2nd and 3rd building phases of the palatium

Tab. 2. Dimension of the area during the building of the palace in the 8th and 9th centuries

	Number of pixels / m ²
Unchanged area	33 773 / 8 443.25
Changed area	51 981 / 1 2995.25
Sum	21 438.5 m ²

In the second analysis fewer differences could be observed. There are also single errors in the raster image (Fig. 28, Tab. 3). The extension process of the palace, which took place between the 8th and 10th centuries, had an influence on some alterations in this area. There were essential transformations in the construction of the church (Saalkirche), in the southern

part of the residence and in the construction of a small church with three conches in the central part of the residence. The changes should be confined to both these areas, however, the interpolated image shows slightly different results. Almost the whole central part of the palatium is marked as a changed area, which probably corresponds with the interpolation errors.

Tab. 3. Dimension of the area during the rebuilding of the palace in the 10th century

	Number of pixels / m ²
Unchanged area	55 588 / 13 897
Changed area	30 166 / 7541.5
Sum	21 438.5 m ²

The first cross section (Fig. 29) shows the elevation and form of the terrain which was prepared for building the palace at Ingelheim. Some of the depressions are illustrated there, namely the foundation trench and a trench for the moat around the residence. The building of the palatium was handled in the analysis as a unique phase, although all the construc-

terrain in some places are quite sharp and rapid. The flat surfaces illustrate the utility level inside the buildings, while the lower area illustrates the moat. In the central part of the palace one can see a kind of water reservoir which is presented with a small depression in the cross section. Despite the modelled level of utility for the individual buildings a natural

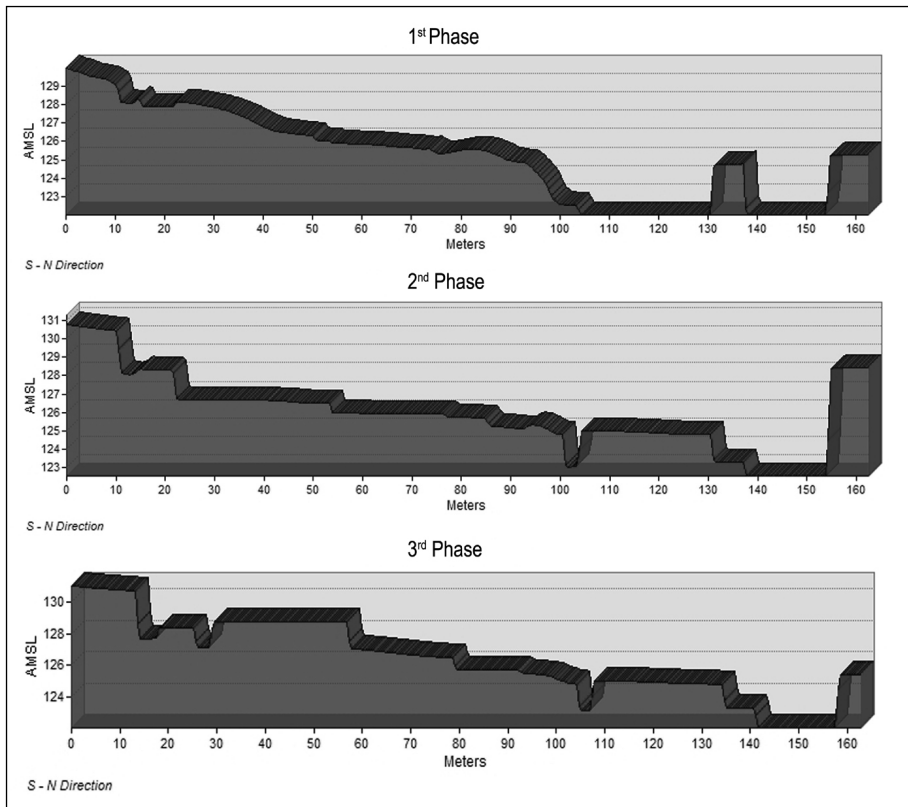


Fig. 29–31. North – south – cross section – the 8th century, the 8th / 9th centuries and the 10th century

tions could not have been built simultaneously. The whole middle part of the profile illustrates a natural decline of the terrain with a small foundation trench for the church with three apses. As can be seen in comparison with other major buildings, the foundation was only slightly embedded in the geological layer.

The cross section for the 2nd phase shows the surface that was shaped almost completely by human activity (Fig. 30). Alterations of the

slope of the terrain in the northern direction is still visible.

Between the 2nd and 3rd phases only limited changes of the terrain are noticeable in the cross sections (Fig. 31). The construction of the church (Saalkirche) is visible in the cross section on the left. The approximate height difference between the church and the surrounding area is about 1 m. Probably, a church was situated on the higher elevation and the

problem of discrepancies of the terrain in the Middle Ages was omitted with a ramp or stairs leading to this building.

There are significant differences between the 1st and 2nd phases related to the building process of the palatium on the cross section which intersects the residence from east to west

the 3rd phase a noticeable error in the interpolation of the area of the residence gate [Ger. *Heidesheimer Tor*] is visible (Fig. 34). The elevated area of a pillared hall located in front of the palace goes smoothly in the direction of the columnar transition, but in fact this should be more abrupt.

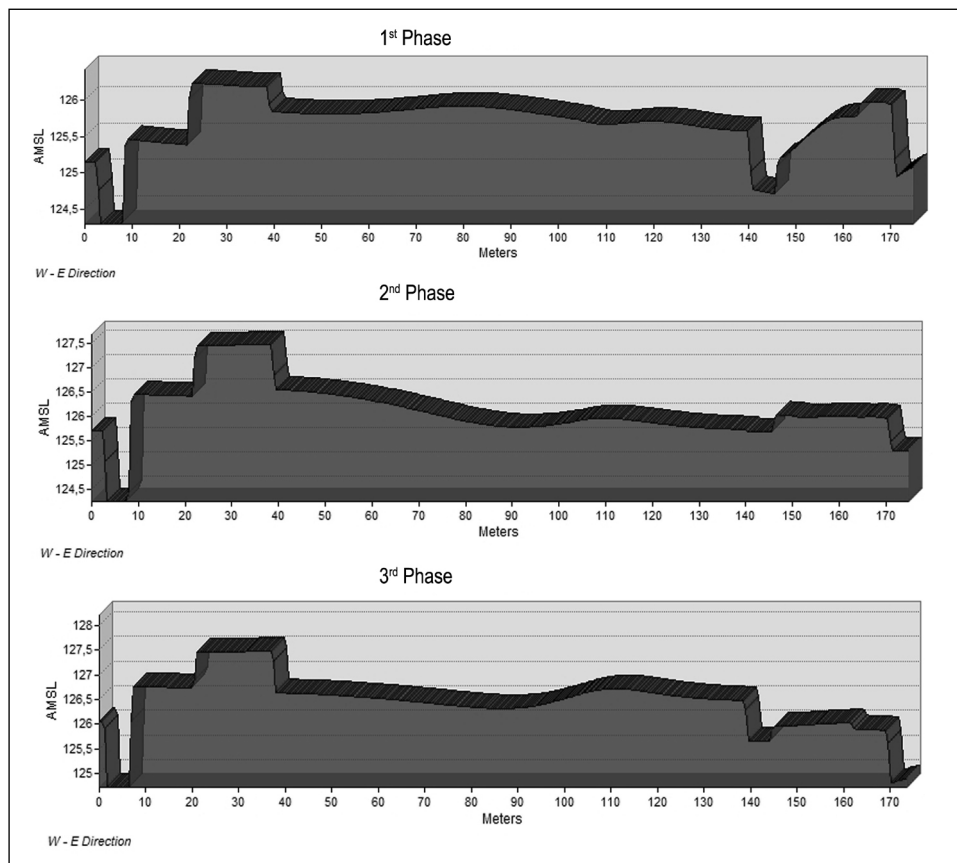


Fig. 32–34. West – east – cross section – the 8th century, the 8th / 9th centuries and the 10th century

(Fig. 32, 33). The first cross section represents a negative depiction of the surface, which was deepened for the foundations of the residence buildings, while the second one is related to the first settlement level. As in the north – southern cross sections, there are noticeable depressions associated with the construction of the residence and the moat. The central part of the illustration shows an inconsiderable change in the terrain. Its slope runs from west to east. In

The differences of the elevation between each phase were also shown with absolute height values the (Fig. 35, Tab. 4). Almost for all sample points in the table the values of the elevation increase. Some of them are probably inaccurate, e.g. for the 1st building phase of the area where lately the church (*Saalkirche*) was built. This is due to the insufficient number of the elevation points for this part of the residence.

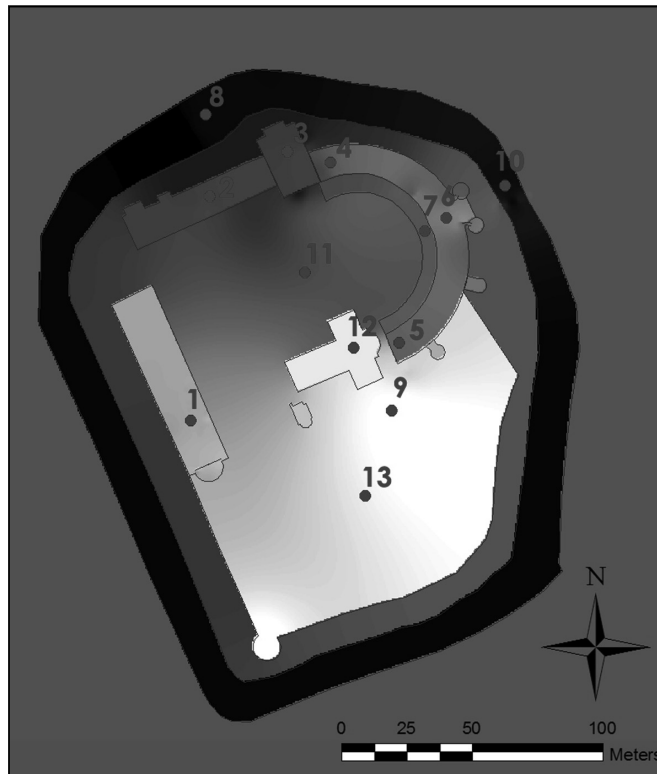


Fig. 35. Location of sample elevation points

Tab. 4. Differences of the elevation (AMSL) for each building phase of the palatium

AMSL for each phase	1 st phase	2 nd phase	3 rd phase
1. Aula regia	126.60	127.50	127.50
2. Northern Part	123.24	124.97	124.97
3. Northern Building	122.01	124.88	124.88
4. Northern Part of the Exedra	123.50	125.71	125.71
5. Southern Part of the Exedra	126.55	127.23	127.24
6. Middle Part of the Exedra	125.66	125.97	125.97
7. Colonnade	124.53	125.65	125.64
8. Northern Part of the Moat	122.01	122.01	122.01
9. Southern Part of the Moat	127.18	127.18	127.16
10. Centre of the residence	125.51	125.72	125.69
11. Area of the Saalkirche	127.10	126.65	128.75

Conclusions

This work focuses on an examination and analysis of the topography changes in the area of the palace in Ingelheim. This is an attempt to prove that an interdisciplinary approach to the subject and a conjunction of the Geographical Information Systems and archaeology can contribute to a better interpretation and analysis of the excavation results. This study was performed in several stages. In the first phase, elevation data for each utility level as well as information to generate the lines of discontinuity were collected. The next stage was devoted to a practical verification of the interpolation methods for the previously collected data. Creation of the models for the various building phases of the palatium was the closing phase of the research. This investigation was completed with an analysis and comparison of the interpolated surfaces.

The presented study was relatively time-consuming. The quantity of archaeological material, which resulted from a hundred years of the research in this area, had a significant impact on this process. The data from which both the elevation points and the boundaries of the various parts of the palatium were acquired consisted of a large number of archaeological and architectural drawings, and reports created during various excavations. A lot of them were available only in an analogue form, which complicated and lengthened the first phase of the study.

Conducting and executing research in a GIS-environment allowed a partial automation and schematisation of this examination. Individual elements of the analysis were combined into a single scheme and repeated for each model.

The use of the cross sections allowed showing the scale and size of the surface changes which was formed by human activities. The shape of the moat and the utility levels of individual buildings are also clearly visible in these images.

Both with map algebra and in the cross sections of the terrain a trend of development and changes in this area were indicated. Although the given number exactly specifies the magnitude of changes, a probability of the occurrence of some errors should be taken into account. One has also to consult the possibility of the replication of the errors in different stages of the study.

GIS proved to be a great "tool" in visualising and carrying out the analysis of the topography changes of the palace in Ingelheim. This system was applied at almost every stage of the research by collecting the data in a database, selecting the methods, applying them and by the final presentation of the results. Methods used by archaeologists and processes which are characteristic of GIS were combined and used, which provides an interdisciplinary approach to the topic and accentuates an important role and interdependence of both these sciences. ■

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Zastosowanie Systemów Informacji Geograficznej w archeologii. Rekonstrukcja topografii średniowiecznego zespołu pałacowego w Ingelheim

Streszczenie

Niniejsza praca została poświęcona zagadnieniu historycznego ukształtowania terenu pałacium w Ingelheim nad Renem. Na topografię rezydencji znaczący wpływ miały zarówno czynniki naturalne, jak i działalność człowieka. Pomimo iż teren pod zabudowę pałacu został w dużym stopniu zniwelowany, naturalny spadek terenu do dziś widoczny jest w topografii stanowiska.

Przedstawione tu zostały rekonstrukcja obniżenia terenu pod fundamenty pałacu oraz wczesno- i pełnośredniowieczny poziom użytkowy (VIII/IX–XI w.). Obszar badań obejmuje teren pałacium karolińskiego oraz ottońskiego, znajdującego się obecnie we wschodniej części Ingelheim (Saalgebiet), miasta leżącego w południowo-zachodniej części Niemiec, w kraju związkowym Nadrenia-Palatynat.

Dane użyte w pracy zostały pozyskane podczas współczesnych badań archeologiczno-architektonicznych prowadzonych w dwóch głównych kampaniach w latach 1963–1971 oraz 1993–2009. Należą do nich punkty wysokościowe i granice obiektów archeologicznych. Dodatkowo cennym źródłem informacji okazały się publikacje dotyczące jednych z najstarszych badań prowadzonych na tym terenie przez historyka sztuki Christiana Raucha na początku dwudziestego stulecia. Do odtworzenia przebiegu fosy wczesnośredniowiecznej, stanowiącej element topografii stanowiska, został użyty zgeoreferencjonowany plan Marks-

burg. Proces georeferencji został uzupełniony o analizę kartometryczności źródła.

Dla pozyskanych informacji przestrzennych stworzona została geobaza w programie ArcGIS 9.2. Wszystkie operacje na danych przeprowadzone zostały również w tym programie.

W drugiej fazie projektu wybrana została metoda interpolacji danych wysokościowych. Znaczący wpływ na wybór metody generowania Numerycznych Modeli Terenu miała możliwość włączenia do procesu linii nieciągłości, w tym przypadku były to granice obiektów archeologicznych i architektonicznych. Kolejny etap projektu stanowiła weryfikacja danych poprzez próbne interpolacje. Do tego celu wybrane zostały dwie metody: metoda krzywej sklepanej oraz metoda odwrotnych odległości. Wykonane modele zostały zwizualizowane w programie ArcScene 9.2 i sprawdzone pod względem swej poprawności. W ocenie wizualno-subiektywnej zostały wzięte pod uwagę następujące aspekty: wysokość danego obszaru względem sąsiadujących przestrzeni, architektoniczną zgodność sąsiadujących przestrzeni, zaburzenia wewnątrz danego obszaru. Dalszą weryfikację oraz analizę porównawczą NMT przeprowadzono za pomocą algebry mapy oraz cięć profilowych.

Niniejsza praca jest próbą zastosowania metod interpolacji do odtworzenia topografii stanowiska ukształtowanego w wyniku dwóch

rodzajów czynników, naturalnych i antropogenicznych. Proces ten starano się zautomatyzować poprzez wybór konkretnej metody generowania Numerycznych Modeli Terenu.

Ważną rolę w badaniach odgrywała kilkietapowość weryfikacji danych oraz zastosowanie Systemów Informacji Geograficznej (GIS). ■

Słowa kluczowe: GIS, GIS w archeologii, NMT (DTM), historyczne źródła kartograficzne, georeferencja, interpolacja, algebra mapy, palatium, Ingelheim

Keywords: GIS, GIS in archaeology, DTM, historical cartographical sources, georeferencing, interpolation, map algebra, palatium, Ingelheim

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