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Paleotopography and anthropogenic deposition thickness of the city of Aachen, Germany

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ABSTRACT
The main objective of this study is to reconstruct the pre-Roman topography under the city of Aachen, Germany. Aachen has a 2000-year settlement history, and enormous amounts of anthropogenic deposits have accumulated during this time; these deposits are thus also visualized. The key data used are archeological excavation records and geological drilling documents that contain elevation and spatial data, and the Kriging algorithm was used to interpolate these data to produce two high-resolution raster datasets showing both the paleotopography and thickness of anthropogenic deposits. The paleo-DEM was then employed to reconstruct the course of former streams running through the study area. This research provides new insights into the topographic preconditions encountered by the first Roman settlers. As the accumulation of anthropogenic deposits in distinct areas of the city is linked to specific historical periods, the results also reveal the developmental stages of the ancient city.

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1. Introduction
The reconstruction of the paleo-landscape and topography in urban areas is challenging, as such areas have often been impacted by humans for several centuries. In addition, intensive building activity and the difficulty in accessing in-situ soils further impedes reconstruction (Holliday, 2004). In rural areas, a wide range of geoarchaeological and geophysical methods can be applied to reconstruct the paleo-topography (Sarris, Kalayci, Moffat, & Manataki, 2018; Van Lanen, Kosian, Groenwoudt, & Jansma, 2014; Westley, Plets, & Quinn, 2014), and surface geophysical methods, such as ground-penetrating radar and geoelectrics, can be used to detect and interpret subsurface deposits and ultimately provide the paleo-topography (Rapp & Hill, 2005). Furthermore, extensive core drillings and subsequent sediment analysis can be conducted (Stein, 1986). However, in urban areas that are densely built up, use of such methods is limited, and geophysical surveys are prone to failure (Rapp & Hill, 2005). Due to continuing settlement activity over centuries or even millennia, the stratigraphy underneath many cities is complex and permeated by interfering structures, such as remnants of historical settlements, power supply lines, sewers, and architectural remnants.

Although coring and trenching techniques also provide useful information about the stratigraphic setting and context (Goldberg & Macphail, 2006; Schultenrein & Aiualasit, 2011), their application is problematic in an urban environment. High building density and transport infrastructure impedes access to suitable areas and drilling campaigns often face legal difficulties. Nevertheless, it is crucial to obtain extensive data to develop a digital terrain model of the topography prior to occupation. Therefore, reconstruction of the paleo-topography of urban areas has to rely mainly on existing data, which are often obtained during archeological surveys and geological drilling in relation to construction activities. Archeological data have occasionally been used in the past to reconstruct the urban stratigraphy for certain ancient European cities and their surroundings, such as Carcassonne, Bourges, Pompeii, Padua, Rome, and Vienna (Carver, 1983, 1987; Edgeworth, Mackert, & Petritsch, 2016; Luberti, 2018; Mozzi et al., 2018; Vogel, Märker, & Seiler, 2011). A map was drawn for the city of Cologne, Germany, showing anthropogenic sediments that have existed since Roman colonization (Brunotte, Immendorf, & Schlimm, 1994), and such mapping was also conducted in a small area of the inner part of the city of Aachen (Keller, 2004).

Based on these preliminary works, the objective of the present study was to reconstruct the paleo-topography and anthropogenic deposits of the historic city of Aachen, Germany (Main Map). To achieve this, data processing was executed through the use of GIS, which allows not only high-resolution mapping of the results, but also enables further processing of an
interpolated digital terrain model. The final aim of this study was to use information provided by the data that enabled certain archaeological and historical issues to be clarified, such as determining the topography prior to permanent settlement and the original drainage lines of small streams crossing the Aachen Basin.

2. Study area

The city of Aachen is located in the western part of Germany near the borders with Belgium and the Netherlands. As shown in Figure 1, the city is situated in the transition area between the Paleozoic rocks of the northern part of the Rhenish slate Mountains and Cenozoic sediments of the Lower Rhine Embayment (Kasig, 2011). The greater Aachen region is characterized by a geological rock formation sequence that ranges from Cretaceous sandstones and claystone in the south to Quaternary gravel and loess deposits in the north. The older Devonian and Carboniferous rocks (from the mountain range in the southern part of the district of Aachen city) are orientated southwest to north-east; they were folded during the Variscan orogeny, which led to the development of several thrust faults within the region (Richter, 1985).

The study area (Figure 1) comprises the entire inner city which lies within the Aachen Basin and covers a total area of 350 ha. The existing Aachen Basin was formed by tectonic activity and fluvial erosion during the Quaternary period and is characterized by four main geological and geomorphological features that are presented below: the alluvial plains of the Johannisbach and Paubach; Market Hill; thermal springs; and the ascending hills that are part of the elevated rim of the Aachen Basin.

The alluvial plains in the Aachen Basin comprise sediments deposited by two small creeks, the Johannisbach and Paubach, which follow a northeasterly direction and run through the city of Aachen: both have their sources in the Upper Cretaceous sands of Aachen.
Forest and are located south and south-west of the research area (Breddin, Brühl, & Dieler, 1960). The alluvial plain consists of loamy sands, clay, and river gravel that was deposited during periodic flooding events. Flint gravel frequently filled with groundwater exists directly below these sediments and causes a high groundwater level in low-lying areas of the Aachen Basin (Richter, 1985). The occurrence of gley soils and lowland fens suggests that ponding and swampy conditions existed in the paleoenvironment of the alluvial plains (Schalich, 1982). Market Hill (Markthügel) is the second important region within the study area. This narrow, southwest-to-northeast trending ridge begins in Aachen Forrest and divides the two streams within the inner city. Market Hill is underlain by relatively resistant folded and faulted Devonian and Carboniferous rocks, and faulting along a south-dipping thrust fault was responsible for a rise in thermal waters that originally formed several springs. The ridge of Market Hill is covered by loess and residual loess with thicknesses of 1–10 m (Richter, 1985). The third important element is the area of thermal springs, which is one of the most important geo-resources in the Aachen region. The Aachen spring group is located alongside the Aachen thrust fault, and the springs are positioned within layers of Devonian decalcified limestone and argillaceous shale from the Frasnium stage (Breddin, 1962; Rüde, 2011). Originally, a total of six thermal springs were located on the south side of the hill; these springs have been tapped since Roman times, although today they are all either sealed or tapped underground to provide a water supply (Pommerening, 1992). The fourth topographic characteristic in the study area is the terrain edges that ascend to the hills enclosing the inner city from the north, west, and south sides. In this respect, settlement development was limited to the inner area of the Aachen Basin until the twentieth century (Curdes, 1999).

In the west and south, the Basin is bounded by the hilly escarpment of the Aachen Forest. The flat-lying sedimentary rocks of this escarpment comprise Cretaceous limestones, marls, and sands, and the lowermost part comprises clayey and sandy layers. In the north, Lousberg hill has a summit that is 100 m above the city, and forms an outlier capped by a thin, hard layer of Vetschauer limestone (Knapp, 1992; Walter, 2010).

The earliest evidence of human presence in the Aachen region relates to the Middle Paleolithic age and is documented by the finding of a very few archeological relics, such as silex hand axes and spearheads (Schyle & Pavlovic, 2011). The first period for which a larger number of relics have been found is the Late Neolithic, and such findings indicate long-term human activity and settlement (Keller, 2004; Weiner, 1998). The subsequent periods of the Copper and Bronze Age are again very poorly represented by archeological findings (Keller, 2004). The first permanent settlement evidenced by archeological findings was founded by the Romans during the first century A.D. (Schaub, 2011). Due to the increased military presence in the Roman province at the Lower Rhine Embayment, medical support for the troops was necessary, and the hot springs in the Aachen Region became a focus (Schaub, 2011; Scherberich, 2011). In the early first century A.D. the first Roman thermal facility was constructed next to one of the hot springs on Market Hill, and a Roman city covering an area of approximately 20–30 ha developed thereafter. This city was built mainly in the eastern part of Market Hill and on the top and on the flanks of the hill. Construction activities intensified, particularly in the early second century, and archeological findings from this era indicate a civilian urban structure with supra-regional significance belonging to one of the largest Roman cities in the Germanic provinces (Schaub, 2011). However, after the decline of the Roman provinces in the fifth century A.D., these areas of Roman settlement were mostly abandoned, and the history of colonization from the late antiquity to early medieval time has not yet been clarified for the city of Aachen (Schaub, 2011). However, it is known that Charlemagne began the construction of the cathedral and his palace complex on top of Market Hill in no later than 790 A.D. (Müller, Ley, Pohle, & Schaub, 2013), and the city of Aachen was then colonized permanently from that time onwards until it reached its current size. The gradual expansion of the settlement area is represented by the visible courses of two city walls constructed in the 12th and 14th centuries, respectively, and approximately 12 centuries of urban history are thus archeologically traceable and have resulted in the deposition of anthropogenic deposits throughout the study area.

3. Methods

The generation of paleo-topography in this study is based on the hypothesis that the last undisturbed state of the surface was in existence until the arrival of the Romans. No pre-Roman human presence has been verified in the study area, and thus no significant impact on the topography has been archeologically determined to date (Schyle & Pavlovic, 2011; Zimmermann, Meurers-Balke, & Kalis, 2006). The objective of this study, therefore, was to detect, as precisely as possible, the first undisturbed natural surface below the Roman settlement layers.

The establishment of a high-resolution terrain model of pre-Roman topography demands an interdisciplinary approach. Therefore, in addition to employing geoscientific methods and working patterns, archeological excavation results, historical information, and engineering geological data were used to collect
appropriate information for use in GIS-based data processing. In this respect, to obtain a sufficient amount of data that enabled detection of the undisturbed deposits and thus the paleo-surface, two main data sources were used. The first source is an archeological excavation documentation dating back to the middle of the nineteenth century and provided by the Office of Archaeological Monument Conservation in the Rhineland (LVR). Several hundred files were screened, and 131 files contained precise elevation data and were therefore considered to be suitable for analysis and thus included. The second source is data from geological drillings conducted within the city area since the 1950s and provided by the Department of Soil Protection of the Environmental Agency of Aachen. These data were either geotechnical reports or subsoil analyses, and a large amount of drilling information exists for the greater Aachen area. However, as with the archeological reports, only a fraction of the data could be included, as the quality of evidence varied. In particular, data often lack information about the exact excavation or drilling site position, or do not provide accurate elevation data. Therefore, only data that provided sufficient information about the spatial location of drill holes and precise elevation information were used. Effectively, information from a total of 1306 bore logs were employed and integrated into the modeling. The data sources were then analyzed with respect to their spatial positions and undisturbed pre-Roman soils and sediments. The total dataset ultimately employed related to 1437 spatial points and related to depth information. The ratio of geological to archeological points was approximately 10:1 (Figure 2). The two data sources complemented each other and were used to obtain the maximum number of high-quality measurement points for the modeling process.

The values were extracted, and the x,y,z coordinates representing the geographical location and the elevation of the site were merged in a table for further processing. In the following, these selected points were used for interpolation of the DEM.

A present-surface DEM (LiDAR-DTM1 with a spatial resolution of 1 m (Land NRW, 2018)) was used as a benchmark for the ground surface data comprising geological and archaeological information. ArcGIS was used for the raster interpolation, and Kriging, which is a geostatistical interpolation method that creates a surface from a set of points with z-values (Hengl & Reuter, 2008; Isaaks & Srivastava, 1989), was considered a suitable method for interpolating the data set. Unlike other interpolation methods, Kriging considers spatial variance and is therefore particularly suitable for an irregular distribution of data points, as in this case (Chaplot et al., 2006).

All 1437 archeological and geological data points were interpolated to a raster using the Kriging algorithm, and the resulting dataset covered a total area of 3.6 km² and encompassed the entire ancient and medieval settlement area of Aachen. This method was applied twice: initially for creation of the paleo-DEM (map A), and then for interpolation of the depth of anthropogenic deposits (map B). Map B (showing anthropogenic deposits) basically consists of values that represent the difference between the paleo-surface and the present-day digital terrain model. The difference between these two surfaces was then extracted from the point data, and point values were subsequently interpolated to a surface. Through the use of a raster calculation, the average deposit thickness for separate zones was determined.

The paleo-DEM was used as the basis for further modeling to reconstruct the former stream courses. Reconstruction was conducted using tools from the ArcGIS-Toolbox ‘Hydrology’. First, sinks of the paleo-DEM were filled to ensure a continuous drainage network of the streams, and a raster showing the flow direction from each cell to its steepest downslope neighbor was then created. Another raster that indicates the accumulated flow into each cell was then created out of this. Ultimately, a raster-dataset was created that showed the potential course of the streams (shown in map A). Finally, for better visualization, the model was converted from a raster to a vector format.

Validation of the interpolated surface was conducted by comparing it with depth data that had not been integrated in the modeling. It was possible to check the actual elevation data of the undisturbed pre-Roman sediments at three excavation sites around Market Hill, and the three validation points were found to differ vertically by 0.09, 0.12, and 0.20 m from the interpolated model.

4. Discussion and interpretation

4.1. Paleo-topography

Map A illustrates the DEM resulting from the interpolation of data points. The spatial resolution is set at 7.3×7.3 m, and the model represents undisturbed pre-Roman topography without any significant human impact. The paleo-topography is shown together with corresponding elements such as alluvial deposits, the location of thermal springs, and the course of streams.

Several interesting observations can be made from the paleo-topography. First, although the elevation of Market Hill existed in the pre-Roman period, it did not have the same height and extension. It can thus be assumed that the first settler considered the hill to be a favorable place as it was located above the marshy alluvial plains. Another interesting characteristic is the large depression on the southern side of Market Hill ridge; this is no longer visible today and was probably formed by fluvial erosion from the thermal spring water.
4.2. Depth of archaeological deposits

Map B shows the difference between the paleo-topography and the modern surface. These anthropogenic layers represent approximately 2000 years of anthropogenic deposition. As evident from the map, the thickness of these deposits varies considerably within the research area (between 0 and 7 m), though variations are by no means uniformly distributed and tend to be concentrated in some areas. The greatest thickness occurs in the central part of the ancient city. The deposits tend to decrease towards the outer parts of the Roman settlement and in the central part of the city, and the thickness of the deposits increases slightly again outside the second city wall. The diversity of deposition thickness can be linked with the age of colonization. For better visualization and interpretation of the results, four major historical zones were classified (zones I-IV) (Figure 3): the Roman settlement area, the medieval town area, the area between the two city walls, and the area outside the second city wall.

Figure 4 shows a cross-section (as indicated on map B) through the research area, where both the paleo-topography and the present topography are visible, and the thickness for each of the historical zones can also be seen.

The highest average deposits (3.0 m) are found in the zone that represents the assumed extension of the ancient Roman town. The second highest value (2.5 m) is found in the area within the first city wall, which encircles the Roman town on three sides, and it coincides with sites where medieval findings are concentrated. Furthermore, there are some areas with higher densities of medieval findings that are located between the two city walls and lie alongside old major roads. It can be assumed that the areas of medieval findings correspond with the approximate extent of settlement until the fifteenth century (Institut für
However, on average, the values between the two city walls are 2.0 m, as major parts of this area were not settled or built-up until the nineteenth century (Curdes, 1999). The outermost part of the second city wall is characterized by a moderate increase (to 2.1 m) in the thickness of anthropogenic deposits. These slightly higher deposition values are attributed to areas of large quantities of World War II debris. As extensive areas of the inner city were destroyed, much of the debris was relocated to outside the city during the reconstruction process after the war (Herwald, Stock, Thiel, & Thoben, 2013).

Observations of the thickness of deposits in combination with the paleo-surface (Figure 4) show a deepening of the pre-settlement surface. This depression could be the result of significant fluvial erosion on the south side of Market Hill in relation to the uprising of thermal springs. These extremely high values of deposition can thus be regarded as an attempt to drain the wet areas and to use landfill to make land flat enough for building.

4.3. Streamflow reconstruction

The creation of a paleo-DEM provides the possibility of computing and visualizing the original steam runs. Two streams once flowed through the research area, and as they have been partially channeled since at least the medieval times (Coels v. d. Brügghen, 1958), the exact original courses of the original undisturbed streams have been unknown to date.

Map A shows the reconstructed watercourses and presents channeled streams. An analysis of the map pattern indicates that the courses of the former streams are located within alluvial plain areas but diverge markedly from the modern courses of channeled streams. However, streams run in two places where no coherent
alluvial plain sediments are indicated. One originates from the north-west and joins the creek at its northernmost point in the study area. This may have been an episodic channel flow resulting from heavy rain events. Due to the low water levels of the streams, it has often been wondered whether (and to what extent) they could have been used for transportation purposes (Schaub, 2011). Thus, with water from an additional inflow, the streams could have been used, at least temporarily (for example for towing small barques).

Another stream section made visible by the reconstruction flows from the south side of Market Hill in a northeastern direction. This course was probably fed by the thermal springs, and as it is the former drainage of the springs, it is thus co-responsible for the depression in the topography in this area. Alluvial sediments in this area testify to an amount of surface runoff.

On the north side of Market Hill, the original course runs approximately 50 m south of the recent course for a length of approximately 350 m. The width of the original alluvial plain was approximately 50 m at this location, and the stream appears to have meandered within these limits until the arrival of the first settlers. From then onwards it came to a backfill of anthropogenic layers on the north side of Market Hill, which led to an expansion of the ridge in a northeastern direction. As a consequence, the ‘Johannis’ creek was forced into a new riverbed further north.

5. Conclusions

The final map shows the original natural surface of the research area and the anthropogenic deposits accumulated on top of it. Our approach shows that it is possible to reconstruct the paleo-surface of a dense urban area using several independent databases and sources. In this study, such sources included both archeological and geological reports, and written historical accounts and maps.

Based on the generated maps we conclude the following:

- In general, the database compiled is considered accurate enough for use in creating a paleo-DEM within an urban area.
- The thickness of anthropogenic deposits can be derived from the paleo-DEM.
- By showing the original surface without human influence, it is possible to reconstruct original watercourses that existed prior to changes caused by settlement activities.
- In addition to the knowledge acquired by creating a high-resolution urban paleo-DEM, specific historical and archaeological insights are enabled. Not only are the topographic preconditions found by the first settlers revealed, but the accumulation of anthropogenic deposits in distinct areas of the city can be linked to specific historical periods.
- An accurate prediction of the thickness of archaeological strata enables the archaeologists involved to make a better estimation of the cost and expected duration of future excavations.

Software

Mapping, modeling, and major parts of data processing were conducted using Esri ArcGIS 10.4.1, and a few raster calculations were made using PCI Geomatica.
The underlying data collection and table analysis were performed using Microsoft Excel 2010 and Access 2010.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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