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Modelling prehistoric terrain Models using LiDAR-data - a geomorphological approach

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ABSTRACT

Terrain surfaces conserve human activities in terms of textures and structures. With reference to archaeological questions, the geological archive is investigated by means of models regarding anthropogenic traces. In doing so, the high-resolution digital terrain model is of inestimable value for the decoding of the archive. The evaluation of these terrain models and the reconstruction of historical surfaces is still a challenging issue. Due to the data collection by means of LiDAR systems (light detection and ranging) and despite their subsequent pre-processing and filtering, recently anthropogenic artefacts are still present in the digital terrain model.

Analysis have shown that elements, such as contour lines and channels, can well be extracted from a high-resolution digital terrain model. This way, channels in settlement areas show a clear anthropogenic character. This fact can also be observed for contour lines. Some contour lines representing a possibly natural ground surface and avoid anthropogenic artefacts. Comparable to channels, noticeable patterns of contour lines become visible in areas with anthropogenic artefacts. The presented workflow uses functionalities of ArcGIS and the programming language R.¹ The method starts with the extraction of contour lines from the digital terrain model. Through macroscopic analyses based on geomorphological expert knowledge, contour lines are selected representing the natural geomorphological character of the surface. In a first step, points are determined along each contour line in regular intervals. This points and the corresponding height information which is taken from an original digital terrain model is saved as a point cloud. Using the programme library *gstat*, a variographic analysis and the use of a Kriging-procedure based on this follow.²⁻⁴

The result is a digital terrain model filtered considering geomorphological expert knowledge showing no human degradation in terms of artefacts, preserving the landscape-genetic character and can be called a prehistoric terrain model.

keywords: LiDAR, digital terrain model, programming language R, kriging, geomorphology, prehistoric terrain model, archeology

1. INTRODUCTION

Geomorphological processes are naturally caused processes which underlie spatial and temporal structures. The relief, as a geomorphological key topic, is exposed to a variety of shape-giving during its formation. Furthermore, the genesis (with few exceptions) cannot be observed directly while taking place.⁵ This is why it is inevitable to take models in to account for explaining certain phenomena. A model which illustrates the land surface is called digital terrain model (DTM). These models are used interdisciplinary to solve various academic issues. One academic field is the archeology.

This research paper is approaching a new method, how to model paleo-surface or historical sites based on a digital terrain model. A high resolution LiDAR (light detection and ranging) data set is used as base for

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the reconstruction of the digital terrain model. Traditionally, filter algorithms eliminate recent anthropogenic artifacts out of the model.^{6,7} How preliminary work for this study shows, is a strict mathematical approach inadequate. Thus geomorphological processes and the character of the landscape are not considered acceptable enough. This is why this paper discusses how geostatistical approaches gathered on the basis of geomorphological and archeological findings, such as certain parameters of the high resolution digital terrain model, can be used to model a prehistorical terrain surface. Considering this, certain work steps were established showing how environmental observations and measurements can be linked with geostatistical methods, so that numerical algorithms can be used to alter the terrain surface without pushing back the landscape-genetic processes.

Considering this, the given paper deals with the archeological request to replica a terrain surface before the first settlement took place. The region of interest is located in the south of Germany near the river Main, which has a long history of settlement.⁸

In this paper a high resolution prehistorical terrain model was generated via geostatistical methods using the software package *gstat*.^{2,3,9}

Therefore the two key points were the application R - for raw data analysis and manipulation - as interpolation methods. For the interpolation the coding language S with its appertained program library is used. In multiple research papers this package is applied.^{10,11} Regarding the work of HENGL ET AL.¹² geostatistics became the main focus in evaluating topographic errors in digital terrain models. Cardinally R is very suitable in case individual issues need to be adjusted and analyzed.

2. GEOMORPHOLOGY, MODELING AND GEOSTATISTICS

A model should be designed to support the empirical research. The main focus in developing a model is to link the data and information to the theory.¹³ This concept is used to develop the here given functions and algorithms.

This work uses geostatistical methods which address geomorphological and archeological subjects. The main focus here is on the geo-component relief, which is the object of investigation. This component is important, because it is particularly marked through endogenous and exogenous forces.^{5,13,14} Many landscape developing parameters can be obtained via analyzing this landscape parameter and can be taken into account for multiple issues. One working appliance of this method is a high resolution DTM generated by airborne laser scanning.^{15,16} Primarily this data acquisition technique locates geo-objects, secondary the data is being processed for mathematic calculations.⁷ The result is a DTM with anthropogenic interferences, such as bridges, road-dams and entire settlement structures. In this case, the terrain model should be used for modeling prehistorically terrain surfaces, it is vital to eliminate the recent anthropogenic relicts. Heretofore, this task has been done by diverse filter techniques. The morphological process is here a common method.^{6,7} The Vosselman-filter calculates with a point-point-relation, which is determined through the difference in altitude. Little differences in height indicate a local ground point. But this technique is for this study rejected because it is calculating on the slope inclination and here it is not possible to deduce a convenient threshold for the drop. In addition this filter method is used for the preparation of the laser scan data.

During the last century high resolution DTM became more and more popular as a survey system or as a macroscopic investigation method regarding archeological issues.^{17,18} One research paper uses this specific instrument as a possibility to identify bomb craters.¹⁹ One new insight of this study was, how high resolution terrain models are capable of identifying small structures in the relief. The advantages of these methods are that they can examine the landscape areas without changing nor affect these. Further it is possible to combine the results with other findings for sufficient analysis. This makes this technique suitable for big scale examinations such as reconstruction of a river course.²⁰

Regarding geomorphological and archeological issues it is reasonable to display the terrain surface without the recent anthropogenic overprint. There are multiple filter to eliminate surface irregularities out of the model.⁷ For example the Vosselman-filter operates with the average slope gradient; nevertheless for a landscape with various slope gradients it is inadequate. In terms of a scientific application this technique is inappropriate for the reconstruction of high resolution DTM, particularly for elimination of different structures in diverse DTM.

Another approach outlines the benefit of geostatistical methods. When there is a statistical examination of geoscientific data it is eligible to regard to them as geostatistic according to SCHAFMEISTER.²¹ An important insight which sustains the geostatistical approaches is the theory of local variables by MATHERON.²² Basically, this theory describes the neighborhood relationship between two variables in an area. This aspect is conceptual for this study.

3. STUDY AREA AND DATA BASIS

The area of interest (ref. Fig 1) has a spatial extent of about 1 square km and is slightly inclined towards the Main.²³

Figure 1. The small town Karlburg has a long history of settlement (ETTEL^{8,24}) and is located in the southwest of Germany. Approximately 25 km away from the City of Würzburg sinisterly along the river Main. The dotted line limits the study area.

For this study a DTM is generated by a laser scan with a consistent arranged grid, with a grid width of 1 meter was utilized. The precision in altitude is $\pm 0,2$ m, the positional accuracy approximately $\pm 0,5$ m. The data was acquired via an airborne laser scanning technique (Landesamt für Vermessung und Geoinformation Bayern²⁵).

4. METHODOLOGY

The for the archeology developed method serves the opportunity to reconstruct landscape areas without any traces of human activities. For that purpose geomorphological knowledge is used, despite the data generated by the DTM. It is common that medieval settlements were built on the terrace level of the Würmian-glacial, which is now approx. 200 m west of the todays flow of the river Main.²³

The designed work steps, necessary for the modeling of a high resolution prehistorically DTM, are shown and described upon that knowledge of the study area. Serving the purpose of the research paper the programming language R and the geographic information system (GIS) ArcGIS are used.^{1,26} The two terrain surface parameters – contour lines and depression lines – are extracted out of the DTM and are managed over the course with multiple data processing steps. Afterwards Kriging is applied on the processed data and further information for interpolation.^{4, 22, 27, 28} The generated model has no trace of any recent anthropogenic artifacts and can

therefore be used for geomorphological and archeological issues, because it contains the typical characteristics of the terrain.

As already mentioned in section 1 it is vital to apply diverse work steps to model the terrain surface free from recent anthropogenic artifacts throughout this study. To implement these steps the functions provided by the program language R are used. This has the main advantage that they can be easily transferred on to different study areas.

Figure 2. Workflow of the individual steps to the prehistoric surface. This is divided in three modules.

To gain a better overview, certain processing steps are conjoined (ref. Fig. 2). The adjustments to the expertise-knowledge is joined in module A and in the module B the adjustment steps for the terrain parameter. During an interim stage these data is fused for interpolation in module C.

The final work step is module C. Following the processing steps and applying the Kriging method, this data is interpolated into a high resolution prehistorically DTM.^{4,27} This new method displays a surface which obtains the same geometric resolution like the input data and serves the settings for the hypothesis.

Beside the data processing and manipulation the interpolation is the main focus of this work. The variogram analysis is adequate for depiction of the spatial correlation and therefore the local variables.⁴ Logic calculations are the foundation of these ties. AHNERT²⁹ claims that the logical correlation has to be in conformity with the physics of nature. A very profound perception for the claim by AHNERT²⁹ is provided by MEIER & KELLER.³⁰ The authors record that spatial structures tend to resonate with nature or to persistence. The assumption is qualified to model spatial issues. There are reasons to believe that the main contour lines such as the main depression lines in the study area have been stable in the past 10 000 years. So that any occurred changes are assumed human caused.

4.1 Data Preprocessing

A normalized preprocess extracts the contour lines and the channels out of the DTM. This step is realized via the ArcGIS software using the exploit Spatial Analyst. The information out of the DTM are required through using the users-library “contour” and “hydrology”. The contour lines are computed with a one meter increment and are

given as a line shapefile. The toolset “hydrology” is used for hydrological analytics within the DTM. This set is developed to model the stream on the terrain surface. To generate the depression lines, basic steps given through hydrological analytics, are required, like to fill in sinks, to drain, the direction of flow, and the accumulation of flow. The depth contours are generated via a simple conditional statement based on the accumulation raster and the output is a line shapefile. This preprocessing step is first in the module B. Furthermore, data is gathered based upon drills, archeological findings and further expertise, those are implemented into the modeling process. Excavation findings and drilling traverse are joined in the model. This information is the input data for the module A (ref. Fig. 2).

4.2 Functions in R

For the entire workflow five functions are developed with the aid of the programming language R. One goal is to enable a simplified handling of the data and reusability of the work steps, with the result to transfer these onto other research areas. Based on the defined data basis, such as drilling data and the expertise four functions are of peculiar interest maintained in the modules: GENPOINTS, AREAIDW, MERGE und REKON (ref. Fig. 3).

Figure 3. Shows the modules, as well as their results. Module A contains expert knowledge, module B the contour lines and depth contours are processed as points and module C are contour lines from generated Prehistoric surface. The function MERGE combines all three modules.

For better handling an algorithm is developed, which is able to import the expertise knowledge. The function IMSHAPES enables importing objects coded in multiple shapefiles into the R-environment. It is irrelevant if these are point, line or polygon shapes (ref. Fig. 2, module A).

Henceforth, this expertise knowledge is processed with the function AREAIDW. The foundation of this function is a multi-level algorithm. In this work, two areas are used where prehistoric surface heights are known provided by archeological findings and drillings. The target of this process is based on the confining coordinates of the raster object with a normal grid distance, via implementing the IDW-Method the interpolation can be executed. This method is a simple interpolation technique.³¹ For the final step, the contour lines are extracted

out of the produced raster field, to be manipulated with the function GENPOINTS. Input object is a point feature similar to the contour lines and depression lines (ref. Fig. 2 and Fig. 3). Afterwards the two objects are fused with the function MERGE.

The preprocessing converts the contour lines and depression lines into line objects. The function GENPOINTS is a two step process and serves the purpose, that the line elements are featured with normalized points, than the equidistant height information is extracted out of the DTM and assigned to the featured point. The output are two data sets which were implemented into ArcGIS and punctually manipulated so that recent anthropogenic artifacts could influence the information of height (ref. Fig. 2 and Fig.3, module B).

Again the MERGE function is applied to tie them all as one object. This data frame maintains three variables. The x-value is represented by the easting value, the y-value is the northing value. Further, the surface height is given by the z-value. For further processing REKON is devised. This algorithm delivers all required information for the program library *gstat*. The function is designed to serve the purpose that, if demanded an estimated raster object of the model is provided (ref. Fig. 2 and Fig. 3, module C).

4.3 Manual adjustment

This step is part of the module B (ref. Fig. 2). The aim of this approach is to eliminate the influences made by mankind. Both shapefiles and their features generated in R are checked on anthropogenic influences. An advantage is given by R being able to manipulate target areas within the line segment. This work step is carried out in ArcGIS. A visual validation is made and in all likelihood point information with anthropogenic nature are deleted (ref. Fig. 4).

Figure 4. Typical anthropogenical disturbed surfaces in the study area; left picture: settlement areas, right picture: roads and bridge artifacts.

The areas of settlement are distinctive (ref. area A Fig. 4). The depression lines are represented via streets. Similar case with the contour line (ref. area B Fig. 4), which are depicted remarkably altered. Different within area C (ref. area C Fig. 4), where the depression line could be a tributary river which flows into the Main, for a long time. Geomorphological research such as historical sources (ref. hist. maps) appoint this. East of the medieval coast line, which is relatively sustained by drills, is irrelevant as height information, because these line bound the area of interest. After this part is accomplished for the depression and contour lines, all further work steps is computed in R (see subsection 4.2).

4.4 Interpolation

As mentioned before in subsection 4.2, the manipulated information is loaded into the R environment fused with the expertise knowledge and saved as a *gstat*- Object.^{2,3} As a necessary step to read the local structures and regional trends, the matrix is converted into a spatial points data frame. The REKON preforms this step (ref. subsection 4.2). The core function of the algorithm is also to eliminate redundant coordinates. Due to the applied method, redundant easting values and northing values are produced. After the input data is prepped with this function, the upcoming steps are carried out with the software package *gstat*.

The first step generates an experimental variogram using the function *variogram*. Therefore the mean variance is calculated for the single groups based on the pair of value. The Lags, meaning the different distance vectors, so as the range of tolerance are automatically generated. Basically, all variograms are divided through lags within the mean semivariance and their containing pair of value. Result of estimation, certain groups of pair- values are similar concerning their distance vector and variances. The software automatically takes care of the requirement that the values calculated within the possible maximum of distance.⁴

In a second step, the spatial dependence is combined with a variogram model in a theoretical variogram by estimating the model function on the record, that corresponds as closely as possible the course of the data pairs from the experimental variogram. The program package provides a variety of such models to estimate the theoretical variogram via the model functions, by adapting a theoretical variogram (model variogram). In practice, some model functions have proven to represent the spatial behavior of the location-dependent variable.⁴ Initially as a model function the Gaussian appeared to be suitable for the interpolation (see paragraph 5).

In this study, after the variographic data analysis the interpolation technique ordinary Kriging (OK) is applied.

5. RESULTS

The foundation of the interpolation were the results created by the REKON function (ref. Fig. 3, module C). Now 8433 features were available for the geostatistical analyses and ordinary kriging (ref. Fig. 5).

Figure 5. The spatial (left side) and statistical distribution (right side) of the points generated. Input data for the interpolation with R.

The histogram depicts the frequency distribution of the generated ground level (ref. Fig. 5). Clearly notable is that the mean of the model is between 160 to 170 meters. The Maximum is 268.5 m, the Minimum is 158.6 m and the mean at 167.6 m. The function REKON eliminated 20 redundant pairs of point values resulting in 3,555,528 pairs of points given in the variogram. The theoretical variogram was adjusted by the Gaussian model function (ref. Fig. 6). This model is very utilizing to meet the geomorphological principles.⁹

Figure 6. Empirical variogram and prediction of the output data (input_KRIGING). There were 3,555,528 point pairs generated.

In the given case an a priori assumption was that the terrain variables are only depending upon them self.

First results, using this method show a definite change in the depth contour (ref. Fig. 7). It becomes apparent that the recent settlements have vanished entirely (ref. Fig. 7, image A, image B). Comparing the contour lines with one another, it is prominent that there disperse in the areas of settlement, such as the bridge. The hillshade is very different. No human artifacts can be seen in prehistoric model (ref. Fig. 7, image C, image D). The resolution of the grid width is the same.

Figure 7. Image A and image B comparison between recent and modeled surface included contour lines. Image C and image D comparison between recent and modeled hillshade.

6. EVALUATION AND DISCUSSION

With Kriging predictions are made that need to be evaluated. These predictions and therefore the quality of the model can be calculated and depicted via statistical cross-validation. The basic idea is to predict a known fulcrum point with the same data and to compare the prediction with the reality. Typical statistical analyses of qualities of DTM, obtained by interpolation, are the statistical parameters mean error (ME) and root mean square error (RSME).³² In this study, the values are -0.015 m (ME) and 0.335 m (RMSE). The ME is in this case zero. Therefore it can be assumed, that on average there is no difference between the measured and predicted values (ref. Fig. 8).

Figure 8. Estimated altitude versus observed altitude.

Another tool for estimating the quality of DTM is the cross-validation.³³ This validation technique compares the measured and the predicted points. A very common technique to survey the quality is the leave One Out Cross Validation (LOOCV).³⁴ This work followed a iterative process and after 100 runs no significant changes occurred any longer, The average of the all-in rate was stable (see table 1).The residues are not following a

Table 1. result of kriging Crossvalidation

	mean error	mean squared normalized error	correlation between ob- served and predicted	correlation between pre- dicted and residuals
expected	0.00	1.00	1.00	0.00
estimated	-0.01	0.23	1.00	0.04

normal distribution, this can be see as a problem. Nevertheless the histogram depicts this, i.e. the Kolmogorov-Sminor-Test is contrary. The p-value shows that after this test no equal distribution exists (ref. Fig. 9). So most likely more dependencies are need to be considered rather than just the ground level (ref. Fig. 9).

Figure 9. histogram of residuals

As displayed the ground level is overestimated in the steep slope areas meanwhile the slip-off slope areas are underestimated. Presumably this effect can be explained by the different point densities. In the case under consideration the point density is higher within the areas with high inclination and small inside the fields with an inferior inclination (ref. Fig. 10). The result can be improved per a better adjustment of the model function. When preparing the points, it should be considered how convenient it is to work with the same point density as in the shallow slope areas.

Figure 10. Cross validation residuals

A further explanation for the statistical results could be, that there were minor or a small number of values of height given in the settlement area. They were completely eradicated so that within the model no fulcrum

points are left. Therefore, algorithms need to be devised to substitute these locations without any value. One possibility would be to replace the missing values by other settlement-free areas, or to connect the deranged contour rather than the depth lines with line segments out of the periphery.

7. SUMMARY / CONCLUSION

The study has shown that it is possible, with the methods described, starting from a high resolution DTM, to model a surface without any anthropogenic influence, where the generic landscape and geomorphological character is not shed. The technique contains preparing, processing and manipulating different data. These were centralized and interpolated by ordinary Kriging. Based on the first results, it is noticed that the quality of the model with the results of the cross-validation (ref. tab. 1) is very high and through the process of interpolation dependencies arise that have not yet been explained by this research study. The few height values inside the settlement areas could have influenced the calculated values. One option could be to substitute the missing values through other settlement-free areas. Or to connect the deranged contour and depression lines with periphery line segments.

The resulting terrain model meets the desire to eliminate recent anthropogenic artifacts from a DTM. The result is a surface, additionally adjusted by expertise knowledge, which can be regarded as prehistoric. In order to enhance the computed model further, diverse research issues should be taken into account. Thus, it is conceivable that additional utilization of other parameters can be an improvement between the recent surface and the result. It is conceivable that the use of additional parameters could lead to an improvement between the nexus of the recent areas and the results. Conceivable given this term, that the focus in the recent model is shifted on temporally stable areas and these constitute a higher reliability in the prehistoric model. For example the shaping elements of the landscape need to be examined more carefully. The consequence would be that the terrain model would not be the only unvaried resource. Another aspect could for validation is to apply a landscape development model.

This work supports the archeological desire to map a particular area without recent human artifacts. The result of this work is even advancing this desire. In further studies this commenced work could be continued, so that the conceptual joins can be taken as an asset in different environmental scientific disciplines.

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