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Knowledge-based modelling of historical surfaces using LiDAR data

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ABSTRACT

Currently in archaeological studies digital elevation models are mainly used especially in terms of shaded reliefs for the prospection of archaeological sites. Hesse (2010) provides a supporting software tool for the determination of local relief models during the prospection using LiDAR scans. Furthermore the search for relicts from WW2 is also in the focus of his research.¹ In JAMES ET AL. (2006) the determined contour lines were used to reconstruct locations of archaeological artefacts such as buildings.² This study is much more and presents an innovative workflow of determining historical high resolution terrain surfaces using recent high resolution terrain models and sedimentological expert knowledge. Based on archaeological field studies (Franconian Saale near Bad Neustadt in Germany) the sedimentological analyses shows that archaeological interesting horizon and geomorphological expert knowledge in combination with particle size analyses (KÖHN, DIN ISO 11277) are useful components for reconstructing surfaces of the early Middle Ages.³ Furthermore the paper traces how it is possible to use additional information (extracted from a recent digital terrain model) to support the process of determination historical surfaces. Conceptual this research is based on methodology of geomorphometry and geo-statistics. The basic idea is that the working procedure is based on the different input data. One aims at tracking the *quantitative data* and the other aims at processing the *qualitative data*. Thus, the first *quantitative data* were available for further processing, which were later processed with the *qualitative data* to convert them to historical heights. In the final stage of the workflow all gathered information are stored in a large data matrix for spatial interpolation using the geostatistical method of Kriging. Besides the historical surface, the algorithm also provides a first estimation of accuracy of the modelling. The presented workflow is characterized by a high flexibility and the opportunity to include new available data in the process at any time.

keywords: geomorphology, historic terrain model, archeology, LIDAR, sediments, programming language R, geostatistics, kriging

1. INTRODUCTION

The request to illustrate various stages of relief development is firmly anchored in geomorphology.⁴ At the same time, the belief that landscape processes can have a major impact on the development history of a region has been established in archeology. In archeology information of this kind is only partially available at present. To analyze the influence of geomorphodynamic processes on the relationship between man and the environment, information is needed, such as how parts of a landscape have to be portrayed in its historical appearance. So archaeological studies/field studies/researches which involves excavation, prospecting, drilling and other analytical methods are implemented and a variety of data is obtained in the course of the studies which can be useful for the interpretation and characterization of landscape processes.^{5,6} In principle, they are categorized into two groups of information that can be used directly or indirectly for the modeling of historical surfaces. So we can talk of qualitative

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expertise when information is especially meant to be recovered from field surveys and the resulting analyzes lead to knowledge and knowledge production. For example, this can be particle size analysis/sediment analyzes used to reconstruct shaping processes (see WOLF & FAUST (2016), Western Mediterranean environmental changes: Evidences from fluvial archives).⁷ Other data are quantitative in nature. They are obtained by measurements and excavations, and they provide results that show the evidence of the vertical profile of a cultural layer. In this specific case these values are converted to elevation data and then directly incorporated in the modeling process.

Especially in areas where classic *quantitative data* is limited or not available, digital terrain models in conjunction with the above mentioned expert knowledge (*qualitative data*) can provide added value by generating *quantitative data*. These may consist of extracting information from a recent elevation model which is suitable to model a historical surface on this basis.⁸

The type of information to be extracted from the DTM depends on the archaeological question to be answered. In the first step, the question of whether it is possible at all to model historical surfaces on the basis of qualitative and expert knowledge of geostatistical analysis of digital terrain models therefore arises.⁹ For this, the principles of geomorphometry serve as a science of quantitative land surface analysis.¹⁰ The synergetic use of different data sources and data types is performed by a multi-stage process that finally leads to a historical surface. The term historical surface refers to a Section of a landscape at a defined time in the past. In this case, a surface is portrayed as it appeared during the time of the first settlement, the early Middle Ages.

The present study aims to model a high-resolution historical terrain surface from a recent high-resolution digital terrain model. Here, the added value lies not only in the visualization of old surfaces but shows possible scenarios of landscape processes. At the same time, a link between the settlement and the geomorphological change is made, which may be helpful to answer archaeological questions. The settlement history is inextricably linked with the development of a river. Conceptually, these geomorphological regions are processed on the basis of *quantitative* and *qualitative data*.

2. STUDY AREA

The study area is part of the 1630 priority program “Harbors of the Roman imperial era up to the Middle Ages” of the German Research Foundation (Deutsche Forschungsgemeinschaft (DFG)). The objective of this project is to research early and high medieval inland ports in Central Europe (see. Figure 1). It is part of the early medieval Salz settlement complex that was moved as the site of the Carolingian-Ottonian salt Palatinate in the center of archaeological research in 2011 through the works of ETTEL ET AL., 2011 and ETTEL & WERTHER 2011 and serves as a starting point for modeling.^{11, 12}

Figure 1. Study area with the partial surfaces. Red dotted line is the course of the historic river. White dashed lines are the location of the historic settlement surface and the whole historical area is represented by the black line.

3. CONCEPT AND DATA BASIS

The basic idea is that the working procedure is divided into two parts based on the different input data (see Figure 2). Conceptually, the historical terrain surface was split into two areas; the historical settlement surface and the historical course of the river (see Figure 1). Based on archaeological field studies on the Franconian Saale in Bad Neustadt in Germany, sedimentological analyzes have shown that cultural layers of archaeological interest and geomorphological expertise in combination with particle size analysis according to Köhn can be used especially to reconstruct all the historical areas of the river and its adjacent surface as it was in the early Middle Age.³ These findings represent the basis of *qualitative data* and were processed from a digital terrain model in the present work with the recent elevation data so that the historical course of the river could be modeled. The basis of *quantitative data* is geoarchaeological drilling core prospecting, archaeological findings and geophysical processes such as that of the superconducting quantum interference device magnetic.¹³

Figure 2. Workflow based on *quantitative* and *qualitative data*.

The digital elevation model has a raster resolution of 1x1 m, which was obtained from an airborne laser scanning. The height accuracy is ± 0.2 m, the position accuracy about ± 0.5 m. (cf. Bavaria State Office for Survey and Geoinformation).¹⁴

3.1 Data basis - Historical settlement surface

The geoarchaeological core prospecting and the findings of the superconducting quantum interference device magnetic are the quantitative basis of data for the historical settlement surface. A wide variety of cores could be obtained in several drilling campaigns by the use of Pürckhauer boring rods and coring tubes. For a first approach, the type of soil (sand, silt, clay) and their depth below the ground surface was determined. In addition to the data from the drilling core analysis, a variety of archaeological evidence was used.^{5,15} Likewise, depth data from the super-conducting quantum interference magnetics device were used.¹³

The height of the recent surface was taken from the DTM. For the archaeological question, the limestone gravel from the C-horizon, representing the culture layer in this case, is of particular interest.⁵ This pleistocene fluvial relocated gravel was transported from the adjacent slopes of Malm in the Saale valley. The C-horizon can therefore be considered as part of an alluvial fan which led to the periglacial area during the last ice age by coming from the south-east river to this area in the Franconian Saale and sediments were deposited at this point in the estuary area. This layer of gravel denotes the historical course of the settlement areas and could be quantitatively identified by drilling.

3.2 Data basis - Historical course of the river

The results of the sedimentological analysis and the resulting findings are mainly based on *qualitative data*. The course of the river could be plausibly reconstructed through particle size analysis from boreholes in the adjacent west region of the historic settlement area. The results of these analyzes indicate that the Franconian Saale was meandering in its lateral behavior in the Middle Ages. A lateral position offset of approximately 15 m to 20 m could be assumed to be relatively plausible. In addition, the width and the depth at that time can be considered to be similar to the recent case. This is also reflected in the geomorphological observations. The present area of the settlement is recently cut through by the Franconian Saale, since it corresponds to an undercut slope. Ultimately, these findings are substantiated by the superconducting quantum interference device magnetic. The first approximations are incorporated in the modeling of the boundary region between land surface and the flowing behavior of the historic river.

4. METHODS

A number of key features and smaller auxiliary functions which can be accessed through a function library have been developed for the implementation. The purpose of this functions is that the information based on the different data basis which can be plausibly linked to each other so that a historical surface can be generated. For this reason, the modeling is divided into two surface areas. One aims at tracking the *quantitative data* and the other aims at processing the *qualitative data* (see Figure 1). The *quantitative data* can be processed more easily than the *qualitative data*. Algorithms that provide the parameters for converting this data into moldable sizes have been developed for the purpose of processing of *qualitative data*. Geostatistical methods are used for the final modeling of historical surface. The implementation of the conceptual foundations was carried out with the programming language R.

4.1 Settlement surface - Quantitative Data

The total range of the historical surface is divided into the historic river area and the historical settlement area (see Section 3). The objective of modeling the ancient settlement area was to model the range of historical surface which served as a settlement area. For this purpose, the relevant boreholes were examined and the amount of soil horizons representing the ancient land surface determined. The height information that had been determined from the geophysical survey provided insights into the behavior of the old surface along the banks of the historic river course. The absolute level of the historic settlement surface (H_{hist}) was determined from the difference between this cultural layer ($h_{culturallayer}$) and the recent surface (h_{recent}). The digital terrain model is based on this measurement (see formula 1):

$$H_{hist} = h_{recent} - h_{culturallayer} \quad (1)$$

After processing, 76 sample points of the historic terrain surface which have been interpolated by the Kriging method were available. To increase the sample point density, the sample points were distributed in a further step on the previously modeled surface. For this, two methods have been applied (see Figure 3). With the geomorphological approach, information including the respective heights of the points on these lines were generated on the historic settlement area of the previously generated contour lines point. The corresponding heights are derived from the previously modeled surface. Therefore 832 sample points were available.

4.2 Historical river course - Qualitative Data

For this part of modeling a qualitative transformation of the *quantitative data* had to be made. This includes for example the historic running behavior of the Franconian Saale, which must be converted into height information on the basis of sediment analysis. Therefore, in a first step, the area of Franconian Saale was extracted from the digital terrain model, which was one of the necessary data basis for this process. Thus, the first *quantitative data* were available for further processing, which were later processed with the *qualitative data* to convert them to historical heights. So for further processing, only heights below 223 m were considered, since they represent the historical course of the Franconian Saale and were of interest for further modeling. The lowest zones of the settlement areas which are closes to the shore are around 221 m and provide information on the approximate

Figure 3. Left: result of the geomorphological approach. Right: result from the statistical approach using the example of the historical settlement area.

depth of the historic river in this area. Therefore, 2 m were subtracted from the extracted grid cells. In a final step, the adjusted height points were shifted about 20 meters west, based on qualitative sedimentological knowledge.

4.3 Implementation of historical settlement surface

The *quantitative data* were available in the form of 76 height measurement points (mainly from drilling core survey and superconducting quantum interference device- magnetic) (see Section 4.1). Since the data collection was carried out in different data structures and reference systems according to the used method, they were then converted to a common data structure in this first step (function: MERGE.AREA). This common data basis was subjected to a first geostatistical analysis (Kriging) as described in Section 4.1 (function: REKON.DF). Evaluations such as an experimental variogram, a histogram or box plot are part of this function. These are intended for a better understanding of the data. For a first preview of the interpolation results it is also possible to generate the historical surface through the application of the inverse distance weighting method.¹⁶ The output of the processed data, such as the variogram are in turn essential for the input parameter of the KRIG.HIST function. The core of this algorithm contains some features from the *gstat* software package.¹⁷ In this function, a validation of the result is integrated alongside the variogram adjustment and the ordinary Kriging which is output in the form of a simple cross-validation and provides a corresponding color coding and the residuals between the measured and the interpolated height values.

The color coding allows a spatial positioning of the residuals in connection with the representation of the histogram. Areas in which the measured values of the model are overestimated or underestimated are therefore visible. The presentation of the validation results allows the user to adjust the input parameters of the Kriging function if necessary. The actual historic settlement surface was displayed as high-resolution grid with a resolution of 1x1 meters.

In a subsequent step, the sample point density of the generated historical settlement area was increased using the approaches described in Section 4.1. The described statistical approach is implemented in the RECU.POINTS function. Here, a regular network of points that include the height information of the historical settlement surface is generated on the previously modeled historical surface. The second approach is based on the contour lines of the historic settlement model (see Figure 3). These were generated with the SUR function. The aim of this algorithm is to analyze the landscape on the basis of contour lines and their natural relief energy. With regard to the characterization of the landscape, it is important to use a step-wise approach to distinguish dominant and less dominant relief elements. Geomorphological findings therefore play an important role on the relief to be examined.¹⁸ The first objective is to Figure out which contour lines are important in order to maintain the natural character of the terrain surface. Both the *nlevels* and *maxpi* parameters are important for this. These parameters control the resolution and reflect the number of extracted contours lines. So the *nlevels* argument reflects the respective number of contour lines and the *maxpi* parameters the maximum number of grid cells

used for extraction. The selected contours points were generated with a defined distance. The GENPOINTS function was used for this purpose. In addition, the interpolation area was interpolated about 3 m in the present course of the Franconian Saale, because based on sedimentological analysis it can be assumed that the recent course is cut by the river (see Figure 3). In the final step, the two packages were merged once again using the MERGE.AREA function.

4.4 Implementation of historic River course

The information on the historical course of the Saale were generated in a multistep process. The aim was to transform the *qualitative data* into *quantitative data* (see Section 4.2). For this, the height information from the digital terrain model were manipulated. The adjustment of the historic lateral location of the river was implemented by the SHIFT function. This feature allows a displacement by a certain amount on the basis of qualitative information. Based on the adjusted point data from the recent model, this feature provides the desired offset of 20 m to the west. In a further step, the heights were adjusted and ultimately converted into regular point information using the RECU.POINTS function as described in Section 4.2. Ultimately 3616 points with the desired characteristic value of the “terrain elevation of the historical river course” were available.

5. RESULTS

For the purpose of the final modeling, the sample points of historical settlement surfaces were combined with those of the historic Saale. Therefore, 5743 points were available for the final geostatistical analyses (see Figure 4). All geostatistical steps could be implemented through the application of the KRIG function. In principle, the variogram analysis can be separated into two phases. In the first phase an experimental variogram is created, which is adjusted in the second phase with the aid of models. This theoretical variogram is then used as basis for the interpolation (see Figure 4). During Ordinary Kriging, the spatial variance of the considered

Figure 4. results of geostatistical analysis. Top left: spatial representation of the interpolation points. Top right: box plot with statistical ratios of interpolation points and bottom left: the experimental variogram and bottom right, the histogram of the interpolation points.

variable is modelled without further information. In addition, the spatial mean a priori is unknown and must be estimated from the data.¹⁹ In order to estimate the theoretical variogram, several model functions were available for adjustment (variogram model). In practice, some model functions have proven successful when it comes to geomorphological issues. These models represent the spatial behavior of location-dependent variables.²⁰ In the present case the “historical ground level” is the variable. In this work, the experimental variogram was adjusted by using a Gaussian function. It is therefore suitable to visualize pedogenic principles.²¹ The result of the

Figure 5. comparison between recent and modeled historical surface. Left: recent surface. Right: model of historical surface. Blue dashed line corresponds to the recent course of the river and red dotted line the historic course. Blue Line Profile 1, black line profile 2, yellow line profile 3 and orange line profile. 4.

interpolation shows a terrain surface having the desired expansion of the settlement area and is lower than the recent terrain surface by about 1 m in accordance with the geomorphological and archeological findings. The Franconian Saale corresponds to its present-day flow behavior, but is however shifted about 20 meters towards the west (see Figure 5).

6. DISCUSSION

The critical examination of the quality of the generated historical surface is based on two approaches. One follows the statistical evaluation and another examined the extent to which *qualitative* and *quantitative data* were taken into account. This approach is named as the geomorphological approach. Based on the statistical analysis, the surfaces (historic river course, historical settlement area) are considered separately.

With the cross-validation a typical validation procedure was used for the statistical validation of models (see WISE 2011²²), which is found in the *gstat* program library among others.²³ If the distribution of the residuals is compared using scatter plots and histograms, two clusters show up in a combined visualization of the settlement area and the river (see Figure 6 left). It therefore seems reasonable to consider these two areas separately (see Figure 6 center, right). When a scatter plot and histogram are compared, slight variations are reflected in the values (see Figure 6). The scatter plot of the total area reveals a dichotomy. Therefore, the historical settlement area and the historic river surface are compared. The historical settlement area, represented by higher elevations, tends to have less variation than the historic river area. It is probably because of the input data (see Section 3). If the river is considered separately, it is clear that the values would fall in the 95% - confidence level (see Figure 6).

When the residuals are shown color-coded, it is evident that the negative values that indicate an over-estimation of the model appear more frequently in the modelled river area. The overall error rate of k-fold cross-validation was close to zero in all models for $k = 100$. Residuals with a mean value around zero that neither significantly exceeded overestimates nor underestimates can be observed on the settlement area (see Figure

Figure 6. comparison between total area (left side), settlement area (middle) and river area (right side). above: the corresponding scatter plot between measured and interpolated height values. below: histograms of residuals.

Figure 7. color coding: comparison between total area (left side). Settlement area (middle). River area (right side).

7). Overall, this shows the inconspicuous spread of the values of the residuals and applies in the visual representation of the historic settlement area by the geomorphological approach. These aspects indicate that there is no systemic error. Over- and underestimation occurs in all areas. Only the characteristic of the variability is different. The reason for this effect might be the different types of data collection and their resulting processing. Thus the bases for the river modeling are irregular unlike the surface of the settlement that was generated routinely and on the basis of the contour lines. This leads to the conclusion that the two areas should be evaluated differently. In order to evaluate the entire historical surface, three statistical indicators were calculated for this accuracy analysis. There was the mean error i.e. the mean (ME), the root mean square error i.e. the standard

Table 1. Results of the accuracy assessment.

	historical surface (overall)	settlement area	river area
ME	-0.0053 m	0.0211 m	-0.0186 m
RMSE	0.1416	0.1464	0.1391
cor_obspred	0.9941	0.9858	0.8313

Figure 8. Heights of the profiles (see Figure 5).

deviation (RMSE), as well as the correlation between observed and estimated height values (cor_obspred) for the three areas determined (see table 1).

The statistical indicators listed in Table 1 describe an accuracy of the historical surface with respect to the available and the incorporated modeling input data. This can be described as very good. However, from a geomorphological/archaeological point of view they give no indication whether the historical surface obtained is also plausible in its form. For this reason, a review based on the geomorphological plausibility is necessary in addition to the strong quantitatively driven assessment of modeling. Therefore a quality assessment based on interpretation of selected profiles was carried out. On the plus side, it provides an interpretation for selected profiles (see Figures 5 and 8). Profile 1 and 2 show the relief, taking into account the *quantitative data* in the area of the historic settlement. Profile 1, parallel to the course of the historic Franconian Saale, is generally based on the measured elevation data. Profile 2 suggests that the model is not located in the embankment area on the measured elevation data. Nevertheless, they are in a tolerable range as the height accuracy of the recent DTM with ± 20 cm is used for comparison. The depth of the historical surface is plausible in both profiles, it is about 1 m below the recent surface.

Profile 3 and 4 (see Figure 8) is aimed at assessing the employed and processed *qualitative data*. Profile 3 shows the behavior of the gravel layer on the basis of magnetic findings (see Section 3.2). It is clear that it is 4 m below the present surface, which seems plausible on the basis of this data, since geomorphological analysis suggest that in the area where the gravel layer is extremely strong, the Franconian Saale runs out or is cut by the river. This thesis is supported by sedimentological investigations. They show that the gravel layer are found on the western side only under powerful alluvial clay layers at a depth of 6 m under the recent ground surface. Profile 4 (see Figure 8) aims to investigate whether the historical course of the river moved 15 to 20 meters in the west direction. It appears in this profile that the river has moved more than 10 meters in the desired direction. Possible explanations for this effect could be that the interpolation had a high impact. The SHIFT function merely displaces the extent of the grid to 20 m but not individual grid cells. Overall, a high quality of the model can be deduced based on all profiles. It implies that, in conjunction with the statistical analysis, the modelled historical surface meets the requirements of use in archaeological context.

7. SUMMARY / CONCLUSION

The present work has shown with the example of the Franconian Saale, that the generation of a historical surface based on a recent digital terrain model is possible. It was shown that different types of data need to be included in this analysis. The distinction between *quantitative* and *qualitative data* thus allows the inclusion of expert knowledge on the geographical features in the modeling process of the historical surface. The subsequent results (historical terrain surface) therefore creates a new data source in the field of archeology. Settlement related questions can be answered on this basis, as they reflect the characteristics of the landscape before the first settlement. So the investigation of an initial relief in terms of geomorphological processes at the early stages, provides the opportunity to answer fundamental questions about the cause of settlement.

Furthermore, relationships between other relief features can be investigated. The procedures and analysis presented in this work can also be used to create surface models that form the basis for landscape simulation models.²⁴ They offer the advantage that they were generated from a geoscientific perspective. This means, that compared to purely numerical methods they are rather based on principles of natural landscape structure (see paragraphs 2 and 3).

It is also possible that the concepts of this work can be useful in the analysis of landscape planning transformations. Possible morphological changes, such as major infrastructural interventions, can be readily assessed and integrated into the planning development.

A change of the relief will also mean that other factors such as runoff behavior and other hydrological processes may be affected and a new process structure will have to be established. This means that other geoscientific disciplines can benefit from the methods developed.

REFERENCES

1. Hesse, R., "Geomorphological traces of conflict in high-resolution elevation models," *Applied Geography* **46**(0), 11 – 20 (2014).
2. James M. Harmon, Mark P. Leone, S. D. P. M. S., "Lidar for archaeological landscape analysis: A case study of two eighteenth-century maryland plantation sites," *American Antiquity* **71**(4), 649–670 (2006).
3. DIN ISO 11277:2002-08, *Bodenbeschaffenheit- Bestimmung der Partikelgrößenverteilung in Mineralböden- Verfahren mittels Siebung und Sedimentation*.
4. Tucker, G. E. and Hancock, G., "Modelling landscape evolution," *Earth Surface Processes and Landforms* **35**, 28–50 (2010).
5. Wunschel, A., Ettel, P., Hein, M., Linzen, S., Roettig, C.-B., Schneider, M., and Werther, L., "Untersuchungen zu einrichtungen der früh- und hochmittelalterlichen binnenschifffahrt ausgehend von den fallbeispielen karlbund und salz in unterfranken," *Häfen im 1. Millenium A. D. Bauliche Konzepte, herrschaftliche und religiöse Einflüsse*, 203–228 (2015).
6. Zielhofer, C., Leitholdt, E., Werther, L., Stele, A., Bussmann, J., Linzen, S., Schneider, M., Meyer, C., Berg-Hobohm, S., and Ettel, P., "Charlemagne's summit canal: An early medieval hydro-engineering project for passing the central european watershed," *PLoS ONE* **9**, 1–20 (09 2014).
7. Wolf, D. and Faust, D., "River braiding caused by rapid floodplain deformation - insights from holocene dynamics of the jarama river in central spain," *Quaternary International* **407, Part A**, 126 – 139 (2016). Progress in Quaternary Archive Studies of the Iberian Peninsula.
8. Höfler, V., Wessollek, C., and Karrasch, P., "Modelling prehistoric terrain models using lidar-data: a geomorphological approach," *Proc. SPIE* **9644**, 96440B–96440B–15 (2015).
9. Schafmeister, M.-T., [*Geostatistik für die hydrogeologische Praxis* -], Springer Berlin Heidelberg, Wiesbaden, 1999. aufl. ed. (1999).
10. Pike, R. J., "Geomorphometry -diversity in quantitative surface analysis," *Progress in Physical Geography* **24**(1), 1–20 (2000).
11. Ettel, P., Werther, L., and Wolters, P., "Der Veitsberg - Forschungen im karolingisch-ottonischen Pfalzkomplex Salz," *Archäologisches Jahr in Bayern* (2011).
12. Ettel, P. and Werther, L., "Archäologische forschungen im frühmittelalterlichen siedlungskomplex salz an der fränkischen saale," *Frankenland* **2**, 79–90 (2011).

13. Linzen, S., Schultze, V., Chwala, A., Schüler, T., Schulz, M., Stolz, R., and Meyer, H.-G., "Quantum detection meets archaeology - magnetic prospection with squids, highly sensitive and fast," in [*New Technologies for Archaeology*], Reindel, M. and Wagner, G., eds., *Natural Science in Archaeology*, 71–85, Springer Berlin Heidelberg (2009).
14. "Digitale geländemodelle," tech. rep., Landesamt für Vermessung und Geoinformation Bayern, Alexandras-
straße 4, München.
15. Werther, L., *Komplexe Systeme im diachronen Vergleich. Ausgewählte Aspekte der Entwicklung von drei
süddeutschen Kleinräumen zwischen Früh- und Hochmittelalter*, PhD thesis, Friedrich-Schiller-Universität
Jena (2014).
16. Chaplot, V., Darboux, F., Bourennane, H., Leguédois, S., Silvera, N., and Phachomphon, K., "Accuracy
of interpolation techniques for the derivation of digital elevation models in relation to landform types and
data density," *Geomorphology* **77**, 126 – 141 (2006).
17. Pebesma, J., "Multivariable geostatistics in s: the gstat package," *Computers & Geosciences* **30**(7), 683 –
691 (2004).
18. Penck, A., [*Morphologie der Erdoberfläche*], J. Engelhorn (1894).
19. Gau, C., [*Geostatistik in Der Baugrundmodellierung - Die Bedeutung Des Anwenders Im Model-
lierungsprozess*], Springer, Berlin, Heidelberg (2010).
20. Akin, H. and Heinrich, S., [*Praktische Geostatistik - eine Einführung für die Bergbau und die Geowis-
sensschaften*], Springer London, Limited, London (1988).
21. Rossiter, D. G., "An introduction to geostatistics with r/gstat," (18.12. 2013).
22. Wise, S., "Cross-validation as a means of investigating DEM interpolation error," *Computers & Geo-
sciences* **37**(8), 978 – 991 (2011).
23. Hastie, T., Tibshirani, R., Friedman, J., and Franklin, J., "The elements of statistical learning: data mining,
inference and prediction," *The Mathematical Intelligencer* **27**(2), 83–85 (2005).
24. Tucker, G. E. and Hancock, G., "Modelling landscape evolution," *Earth Surface Processes and Land-
forms* **35**, 28–50 (2010).