Towards Unleashing the Potential of Elevation Data for Archaeological Research

Reviewing Past and Present Applications

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Abstract: Since the first years, elevation data has played an important role in many contributions presented at the conferences in Vienna. The 25th conference which formerly had the German title “Archäologie und Computer” and now is known as “Cultural Heritage and New Technologies” is the occasion for looking back on early archaeological applications of digital elevation models (DEMs), advances in the course of time, the state of the art and future developments. Many of the approaches presented rely on elevation data grids that are generated from irregularly distributed altitude points. Before the first conference in Vienna, several high-impact papers dealing with elevation data were published. In most cases, their goal was to create predictive models, i.e., to delimit areas of high probability for detecting an archaeological site. Attributes derived from elevation data such as slope, aspect, view quality and shelter were often used as predictor variables. The papers presented at the Vienna conferences are evidence of the fact that archaeological predictive modelling is a highly controversial topic. Additional contributions at the conference in Vienna are revisited that deal with retrodictive modelling, i.e., explaining the distribution of known sites based on landscape properties, with predicting (or retrodicting) the location of linear features such as roads or boundaries, and with issues of low-resolution digital elevation models. Moreover, contributions at the Vienna conference are highlighted that reflect the development of applying high resolution elevation data for detecting archaeological sites. The examples presented are supplemented by some illustrations from the author’s and her colleague’s work in the Rhineland.

Keywords: *Digital Elevation Model—GIS—Lidar Data—ALS Data—Predictive Modelling*

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Introduction

Looking back at the first conferences on computer applications in archaeology (with the German title “Archäologie und Computer”) held in Vienna, the papers employing complex analysis of elevation data have impressed and inspired the author most. A substantial number of contributions presented in Vienna have dealt with advances in this research area in the course of time irrespective of the fact that the conference changed its name. This paper looks back at the developments before the first conference in Vienna was held and continues to highlight relevant aspects of this topic, nearly all of these were presented at the annual cultural heritage conference in Vienna. The selection of contributions revisited is subjective, and a substantial portion reflects the author’s own work presented in

Vienna or performed at the Rhineland Commission for Archaeological Monuments and Sites in Bonn, Germany. Due to time and funding restrictions, this work mostly relied on elevation data not recorded for archaeological purposes. The main goal of this paper is to give an overview of the state of the art of elevation data processing and lessons learnt, some of which run the risk of oblivion due to the fairly long timespan since their first publication.

Figure 1 presents an overview over the concepts and advances in elevation data use in archaeology. These aspects are discussed in more detail in the chapters below. Figure 1 also illustrates that some concepts evolved with time. For instance, interpolation was at first mainly employed for generating a raster digital elevation model (DEM) from contour line points digitized from paper maps; later, at a different scale, interpolated surfaces were generated from ground points measured by Lidar (light detection and ranging).

The focus of the next section of this paper is on early archaeological applications of elevation data in the 1980s and 1990s. Many attributes derived from elevation data such as slope and aspect were already used in the early papers. These attributes are important building blocks of the first complex GIS application in archaeology, which is known as predictive modelling (PM) and discussed subsequently. The aim of this set of methods applied in cultural heritage management is to delimit areas of high probability for detecting an archaeological site. Potential and limits of PM are discussed, highlighting a paper presented at the Vienna conference in 1999. PM is closely related to retrodictive modelling, i.e., explaining the distribution of known sites based on landscape properties. A paper at the CHNT19 conference applied retrodictive modelling for medieval settlements in a hilly region based on several attributes derived from elevation data. The early PM applications focus on point data. Approaches for predicting (or retrodicting) the location of linear features such as roads or boundaries were presented also at the conferences in Vienna. Another section of this paper discusses issues with elevation data at a scale typically used for landscape analysis. These include generation of elevation data grids from contour line data as well as accuracy and resolution of the point or grid data. The issues are illustrated by examples from the Rhineland and some of the results presented on a poster at CHNT20.

Since 2004, the use of digital elevation data for detecting archaeological features has been an important topic at the Vienna conferences. High-resolution elevation data is required which is mostly recorded by aerial laser scanning (known as ALS or Lidar data). This data gradually became readily available in many European countries. Shallow features require refined visualisation techniques, some of these are exemplified by recent applications from the Rhineland. Finally, the discussions of the previous chapters are summarised and issues with ALS data are reviewed. Although machine learning approaches for analysing elevation data were already presented at the Vienna conference in 2005, these applications have become more widespread only recently (CHNT conference in 2019). Currently, the types of archaeological features that were used as test cases in the machine learning approaches based on ALS data are limited. But in future, this will most probably change, and the author is looking forward to new talks on this topic at future CHNT conferences.

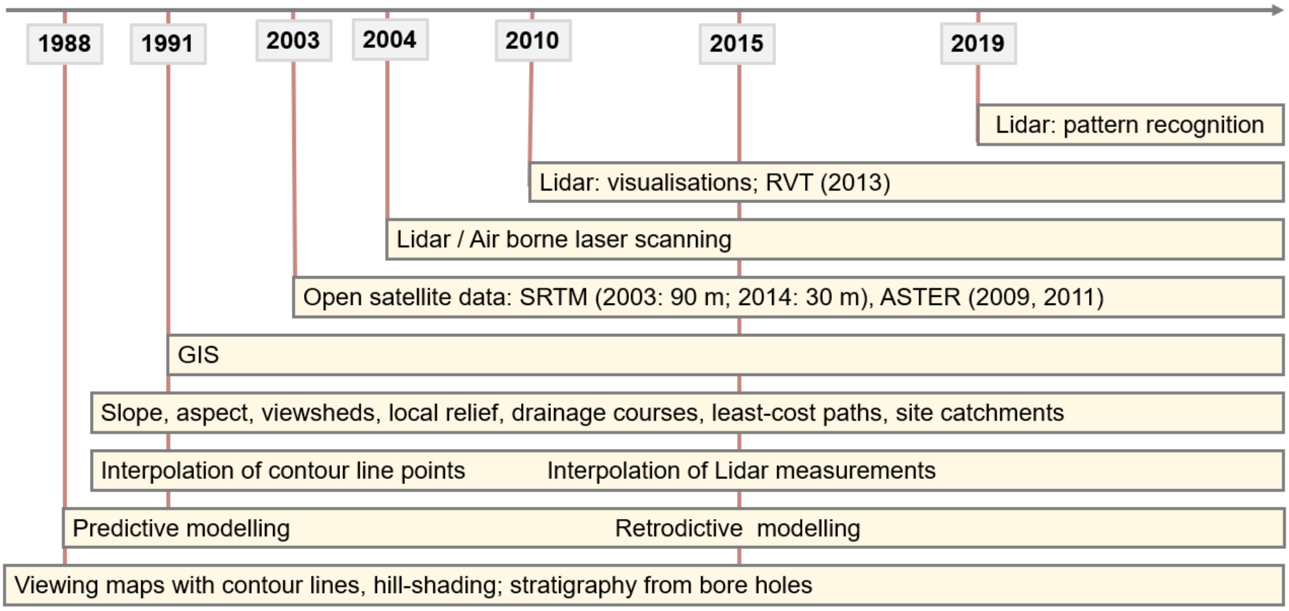

Fig. 1. Timeline: use of elevation data in archaeological research (© Irmela Herzog)

Looking back at the 1980s and 1990s

Before digital elevation data covering large parts of the world at different scales became available, archaeologists used contour lines on analogue maps to identify possible site locations and to assess the risk of erosion for known sites (Fig. 1). These are some of the reasons why scanned maps with contour lines at a scale of 1:25,000 were integrated in an information system with a GIS component for archaeological sites in Saxony, Germany, presented at the Vienna conference in 1998 although more accurate topographic maps without contours were also part of that system (Zeeb, 1999).

An early application of elevation data for archaeological research is presented in the publication by Kvamme (1988). He used elevation data digitized from contour maps in the 1980s with the aim of developing and testing “models of archaeological distributions that have a predictive capacity”. The paper includes descriptions of how to derive slope and aspect from a contour map and mentions two approaches for comparing aspect measurements in view of the 0°=360° issue. Kvamme also presents key figures for measuring local relief, terrain texture, view quality and shelter. Moreover, he refers to the publication by Ericson and Goldstein (1980) for estimating travel time based on slope. So, this paper touched many subjects that are important for state-of-the-art archaeological landscape research in hilly or mountainous terrain today. The use of elevation data for PM became fairly widespread in the years after Kvamme’s publication especially after GIS software became popular.

Kvamme also is an early adopter of GIS software that provides tools for calculating the key figures mentioned above (Kvamme, 1992). After generating a DEM grid based on digitized contour line data, GIS allowed him to generate viewsheds as well as 3D visualisations of the terrain that highlight the location of finds or sites. In his papers, he also suggests a new DEM based approach for identifying drainage courses. The proceedings volume containing Kvamme’s GIS papers also includes a contribution by Gaffney and Stančič (1992) that presents site catchments. These are derived from slope-dependent cost surfaces, i.e., rely on elevation data as well.

Subsequently, archaeologists all over the world have adopted, discussed, or improved these approaches. An example is the PhD thesis by Axel Posluschny (2002), parts of which were presented at the Vienna conference in 1999. The thesis includes several analyses based on data derived from a DEM: preferred ranges of elevation, slope, and aspect are identified for the sites considered; the thesis also discusses site preservation and detection probability depending on the local relief key figure.

Predictive and retrodictive modelling

Posluschny used typical PM approaches, a set of methods “for projecting known patterns or relationships into unknown times or places” (Warren and Asch, 2000), one of the earliest complex applications of elevation data in archaeology (Fig. 1). His main goal was to understand past land use. In cultural heritage management, the aim of PM is to reduce the effort for surveying a complete area by identifying areas that are most likely to contain relevant archaeological remains (Verhagen et al., 2006; Whitley, 2004). As a result, heritage managers, planners and designers are provided with appropriate cartographic tools: “not just maps showing the locations of currently known archaeological sites and monuments, but also maps indicating where to expect archaeological material” (Kamermans et al., 2004).

The early approaches relied on two assumptions: “first, that the settlement choices made by ancient peoples were strongly influenced or conditioned by characteristics of the natural environment; second, that the environmental factors that directly influenced these choices are portrayed, at least indirectly, in modern maps of environmental variation across an area of interest” (Warren and Asch, 2000). Several Dutch researchers applied PM techniques already in the 1990s and presented a discussion of the results as well as approaches for improvement at the CHNT predecessor conference in 1999 (Verhagen et al., 2000). They point out violations of the second assumption of PM techniques outlined by Warren and Asch (2000) due to bias by research intensity and changes of relief and pedology since the period considered as well as post-depositional disturbances. Moreover, they underline the importance of previously existing man-made landscape elements such as roads for choosing a site location for some periods of the past. These attractors are not in accordance with the first assumption of PM approaches as defined by Warren and Asch (2000). Additional issues raised by this group of authors with respect to previous approaches in the Netherlands are lack of temporal resolution and of distinction between site types such as settlements and burials. The progress in this discussion is reflected in two additional papers presented in Vienna in 2003 (Kamermans et al., 2004) and 2005 (Verhagen et al., 2006). The researchers come to the conclusions “that predictive modelling is an issue that is far from ‘solved’”, that “academic and public archaeology in the Netherlands are still opposed when it comes to predictive modelling”, and that these issues could be addressed by providing a measure of the uncertainty for the PM results. The Dutch debate and some contributions by British colleagues (summarised by Wheatley and Gillings, 2002, pp. 179–180) inspired a contribution by the US based archaeologist Thomas Whitley (2004) at the CAA conference held in Vienna in 2003. He observes that PM approaches often achieve success if they are based on “limiting factors on all human behavior; primarily slope and distance to water”.

Although digital elevation data did not play an important role for the early Dutch predictive models due to the mostly level ground in this country, early PM applications in other parts of the world relied partly on elevation data and derivatives thereof (i.e., slope, aspect, indices of ridge/drainage, local relief) as well as on geological and soil data (Wheatley and Gillings, 2002, p. 167). An example is the PM of settlements in a region in the Czech Republic presented at the “Archäologie und Computer” conference in 2002 (Golan, 2003). The issues discussed by the Dutch group are relevant for these predictive models as well. Golan (2003) did not only include elevation, slope, aspect, local relief and shelter quality in his analysis, but also cost distances to water courses, forts, and geological features. Unfortunately, the paper does not give any details on the cost-distance computations, but typically, cost-distances are derived from slope (i.e., from elevation data, see below).

A variant of PM is site location analysis also known as retrodictive modelling, that is explaining the site distribution based on landscape data. Typically, the landscape variables used for retrodictive modelling do not differ from that used for PM. An example of retrodictive modelling for settlements in a rural hilly study area east of the Rhine was presented at the CHNT19 conference (Herzog, 2015). Figure 2 (left) is based on a list of place names that indicates for each settlement the year when it was first mentioned. For the settlements mentioned before 1601 AD, four strong impact variables were identified by retrodictive modelling: soil quality, slope, local prominence and least-cost distance to flow accumulation. The latter three variables were derived from a DEM.

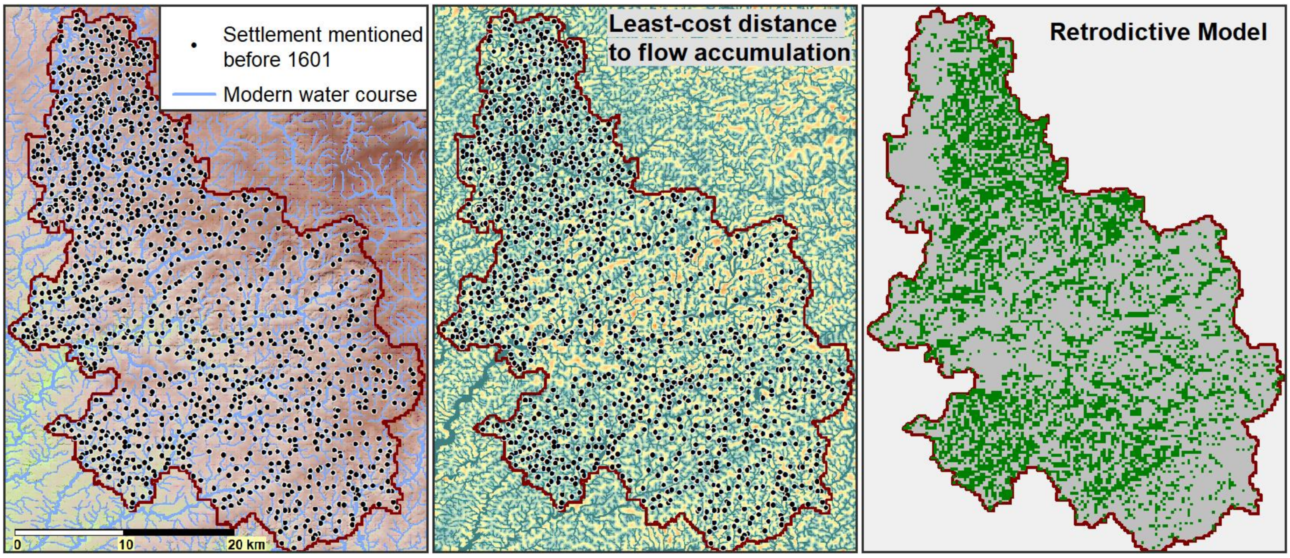

Fig. 2. Left: Study area east of the Rhine with dots representing the settlements mentioned before 1601 AD, background: DEM and water courses; Centre: Least-cost distance to flow accumulation (blue = close to water course); Right: Retrodictive map, green cells with a cell size of 250 m indicate high retrodictive values. (© Irmela Herzog)

Retrodictive modelling based on a complete set of sites (e.g., settlements) also allows assessing the accuracy of PM approaches. This was performed for the case study presented above. The retrodictive model shown on the right in Figure 2 depicts green patches where the four strong impact variables indicate favourable conditions for settlement. According to Warren and Asch (2000), “a successful predictive model is one that minimizes classification errors (site versus nonsite) to such an extent that it offers a substantial gain in accuracy over null models arising from chance alone”. This gain can be assessed by a performance indicator proposed by Kvamme, with values in the range of 0 to 1 (Warren and Asch, 2000; Wheatley and Gillings, 2002, p. 178). Gain values close to 1 indicate high predictive utility. According to Whitley (2004), “a good predictive model should achieve a gain statistic at least above 0.5”. Whereas Wheatley and Gillings (2002, p. 178) refer to a predictive model with a gain of at least 0.8, the gain of the retrodictive model presented in Figure 2 is 0.41. Considering the high settlement density in the study area with hardly any gaps, the latter gain value is probably close to the maximum that can be achieved.

In retrodictive modelling, when all site locations are known, spatial patterns (e.g., minimum distance to the neighbour, adequate farming plots for each farmstead) can be analysed. These patterns as well as the size of settlements are important aspects when reconstructing past landscapes, but including them in a PM approach is a very complex but feasible task (e.g., Bevan and Wilson, 2013).

The predictive and retrodictive models discussed above rely on known sites. In contrast, deductive approaches can derive predictor variables from theoretical considerations (Wheatley and Gillings, 2002, p. 169). An example for such a deductive approach was presented in the best student paper at CHNT24 (Rom et al., 2020). The authors of this paper assume that the sites in their study area in Lebanon can be found on hilltops with a certain size and circularity. The site candidates were identified using elevation data recorded in the course of the project. Aerial photographs were used to validate site candidates.

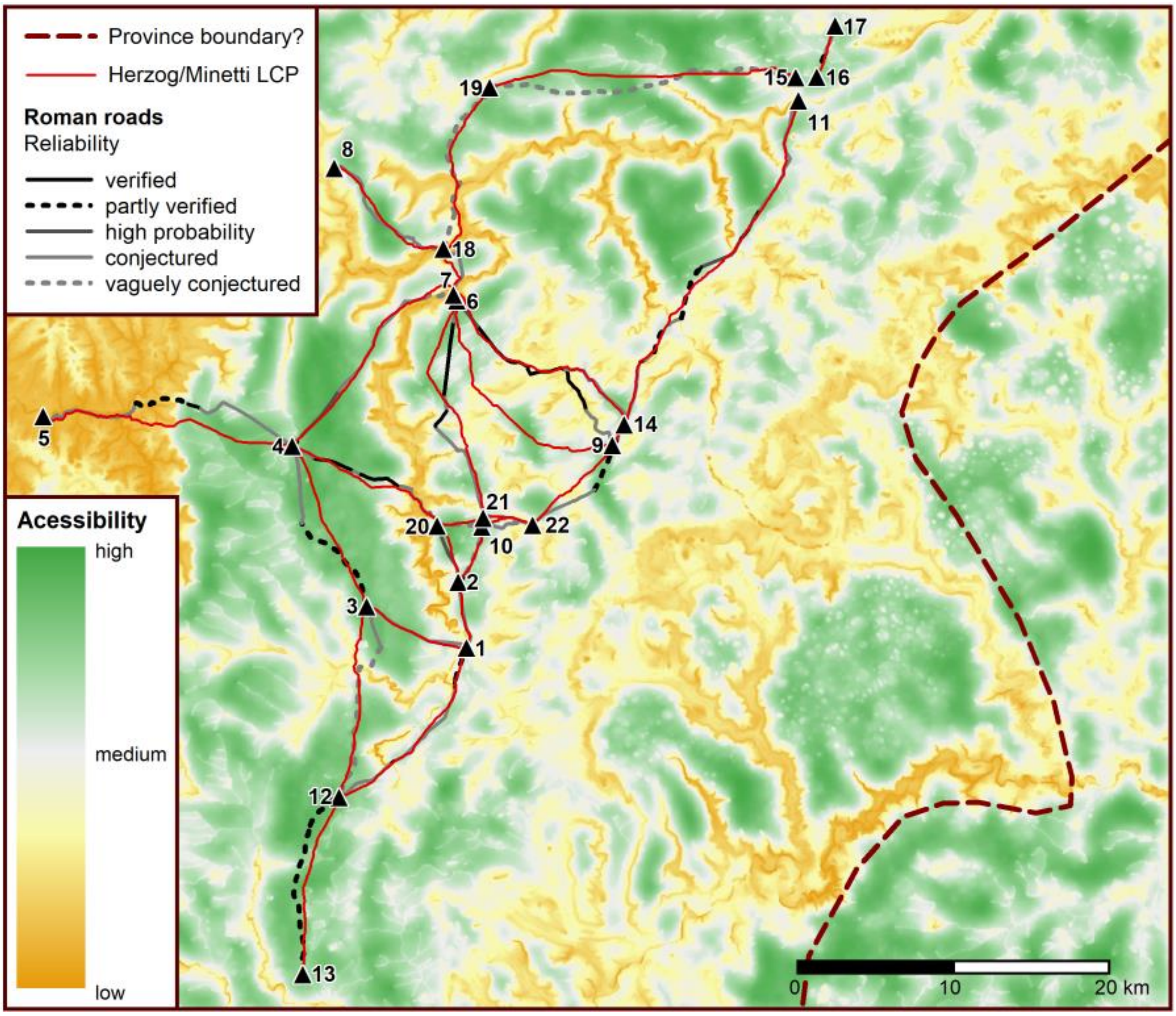

Fig. 3. Roman roads, classified according to reliability, reconstructions by least-cost paths (LCP) and a hypothetical boundary. Background: Accessibility map for cost function Herzog/Minetti (© Irmela Herzog and Sandra Schröer)

In the early days of PM, the extent of the site was not considered, instead the analysis relied mainly on point data (e.g. Golan, 2003; Warren and Asch, 2000). Obviously, this is not appropriate for linear features such as roads, water pipelines or boundaries, which is illustrated by the case study by Münch (2007) presented at the Vienna conference in 2006.

Least-cost path (LCP) computations are frequently applied in order to reconstruct past routes. The cost function typically depends on slope, sometimes combined with other factors such as viewsheds or water courses. As mentioned above, the computation of viewsheds and of likely water courses (by flow accumulation algorithms) are also based on elevation data. Since the first least-cost approaches (e.g. Gaffney and Stančič, 1992), the number of slope-dependent functions applied for reconstructing paths and roads has increased considerably, and some of them require the selection of parameter values. For instance, the poster by Herzog and Schröer, presented at CHNT 22, (paper published in 2019) tested four slope-dependent functions for walkers and another function for vehicles that has a critical slope parameter (three critical slope values were tested). The aim was to reconstruct a set of Roman roads in southern Germany. Figure 3 shows the result of the most successful reconstruction of the roads by LCPs.

For reconstructing the boundaries of a site, site catchments relying on a cost surface are often applied. Most of these cost surfaces are derived by attributing costs to slope. An early example by Gaffney and Stančič (1992) was mentioned above. Thiessen polygons have been used for reconstructing boundaries based on the assumption that there is no empty space between the territories considered (Conolly and Lake, 2006, p. 211). Slope-dependent least-cost variants of Thiessen polygons were computed by Herzog and Schröer (2019), the centres are probable Roman capitals of administrative units in southern Germany. Figure 3 shows another approach for identifying possible boundary locations: boundaries are mostly found close to low accessibility areas. The accessibility map in Figure 3 was also computed using elevation data, details of this approach can be found in the publication by Herzog and Schröer (2019).

Issues with elevation data

Several archaeologists in Germany admired advances in PM in the Netherlands and other countries in the 1990s and considered starting similar projects. Being aware of the substantial landscape change in the Rhineland area due to human impact including open-cast mining, other mining activities, motorways, quarries and dams, two projects were initiated in the Rhineland with the aim of investigating the reliability of the altitude information on maps that were created before most of these landscape modifications had taken place.

In the first project, Lechterbeck (2008) compared the DEM derived from contour lines on maps created in the late 19th century (scale ca. 1:25,000) with that of a DEM with a grid size of 10 m based on Lidar and photogrammetric data acquisition. Only part of the differences in elevation could be attributed to anthropogenic impacts. In forested areas, visibility was restricted, this impeded elevation measurements using the technologies available in the 19th century ensuing substantial errors. Therefore, the elevation data on the late 19th century map set is at best useful in areas of agricultural use at the time of map making.

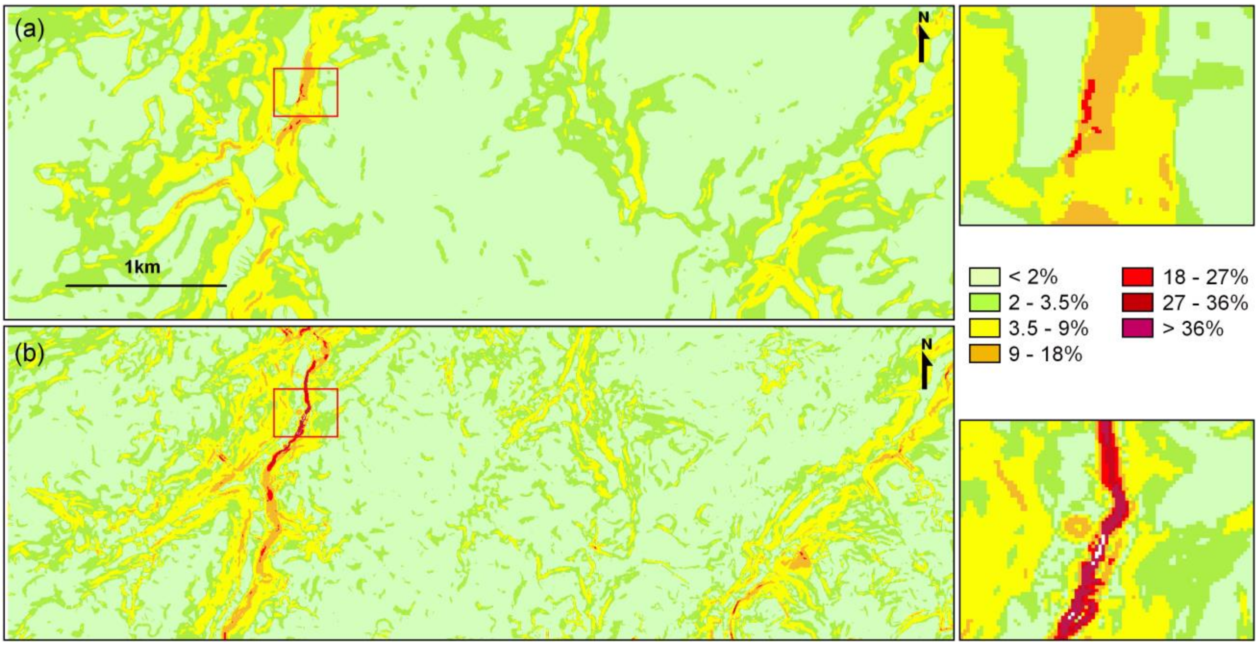

Fig. 4. Slope maps for the Merzbachtal, west of the Rhine in the Rhineland. (a) derived from contour lines on late 19th century maps at a scale of 1:25,000, (b) based on contour line maps at a scale of 1:5000 created in 1955. (© Irmela Herzog and Ana Judith Largo Arias Marek based on geodata provided by Geobasis NRW)

The aim of the second project by Herzog and Largo Arias Marek (2009) was to reconstruct the old surface in areas of open-cast mining west of the River Rhine. Due to the known issues with the late 19th century maps, contour line maps at a scale of 1:5000 created in 1955 were purchased from the ordnance survey institution in the Rhineland (Geobasis NRW). The contour lines were digitized semi-automatically and raster DEMs created from this data. Unfortunately, the 1:5000 contour line maps were not available for all parts of the study area. Therefore, the 1:5000 DEMs were compared to those derived from the late 19th century maps, hoping for limited errors in the study area where agriculture prevailed at the time when the maps were created.

The differences in elevation were acceptable in the study area (mean: 1.07 m). But due to the differences in scale, the DEM derived from the late 19th century maps is smoother. This has a dramatic effect on the slope maps derived from the two DEMs (Fig. 4). The classification of slopes in Figure 4 is based on a scheme for agricultural use. The slope map of the smoothed DEM (Fig. 4a) indicates a larger proportion of arable land than the slope map in Figure 4b.

A similar effect can be observed when reducing the resolution of a DEM due to computational load in a large study area. A case study in the highlands of Ecuador by Herzog and Yépez (2016) presented at CHNT20 compared SRTM 3” (grid size ca. 90 m) and SRTM 1” (grid size ca. 30 m), these are two freely available DEMs based on satellite measurements. Table 1 shows the distribution of the slope values of the two DEMs for the study region considered. In this region with steep slopes, the slope of half of the terrain exceeds 44.8% when slope is derived from SRTM 1” data; for the slopes derived from the SRTM 3” DEM, this median value is considerably lower (37.2%).

Table 1. Differences in the distribution of the slope values (in percent) for the two SRTM elevation grids

DEM	**1st quartile (25%)**	**Median (50%)**	**3rd quartile (75%)**
SRTM 1”	27.6	44.8	64.0
SRTM 3”	23.7	37.2	53.1

As mentioned above, contour line data is an alternative to freely available satellite data in many cases, for instance if working with old maps or if the contour lines provide a higher accuracy. In the case study by Herzog and Yépez (2016), the digitised contour lines of the official 1:50,000 maps provided by the Military Geographical Institute of Ecuador resulted in a more accurate DEM than the satellite data. Typically, DEMs derived from contour line data exhibit spikes in the histogram of altitudes and 'tiger-striping' of the slope map (Conolly and Lake, 2006, p. 105; Wheatley and Gillings, 2002, pp. 116–119). Filters resulting in a smoothed DEM may remove most of these unwanted effects; but as mentioned above, smoothing will no longer show abrupt changes in slope and underestimate a considerable portion of the slopes.

Landscape surface modifications are not only caused by bulk material extraction at a large scale, building projects, and erosion. Verhagen et al. (2000) describe changes in the relief of the Netherlands due layers of peat dating to the Medieval period. In some areas, the peat layers were exploited for fuel in the Late Middle Ages and later, resulting in substantial variations in the depth of the soil layer covering earlier remains.

DEMs for detecting archaeological features

The resolution of a DEM is vital for the detection of archaeological features. At the CAA conference in Vienna in 2003, Beex (2004) pointed out that the Nyquist limit determines the minimum size of features to be detected on the DEM surface: to identify a circular pit with a diameter of 20 m in a DEM, the maximum distance within the set of altitude points forming the basis of the DEM should not exceed 10 m, and 5 m is the recommended maximum distance. Interpolation of irregularly distributed elevation points resulting in a high-resolution DEM grid may obscure large gaps in the set of elevation points. These issues are also relevant for ALS data as outlined below.

At the 9th conference "Archäologie und Computer" in 2004, two papers focused on the detection of archaeological features based on elevation data. The contribution by Gerlach et al. (published in 2008) used a fairly coarse DEM with a grid size of 10 m to detect the remains of large bulk material extraction pits, that were partly refilled. A large proportion of these pits were created by the brickmaking industry and its precursors. The earliest brickearth pits are of Roman origin, but most of these features date in the 19th and early 20th century. These brickyards were clustered in the western part of the Rhineland. As most pits were nearly completely refilled, it was hardly possible to detect them in the field. DEM visualisations by colour-gradients depicting altitude change or by contour line plots proved not very useful for identifying the pits in non-level areas. Hill-shading visualisations were more successful (Fig. 5). Artificial cross sections allowed assessing the depth of these features, which often did not exceed 1 m for a former pit with a diameter of about 50 m (Fig. 5). These pits are important because they often had (partly) destroyed archaeological features dating back to earlier periods. Moreover, the material in the pits had been relocated and the refill material probably originated from somewhere else. Consequently, the prehistoric finds identified during field walking are not a reliable indicator of a prehistoric site, if the soil including the finds was transported to this location for pit refilling purposes. Many earlier archaeological features can be detected by similar approaches using DEM grids with higher resolution.

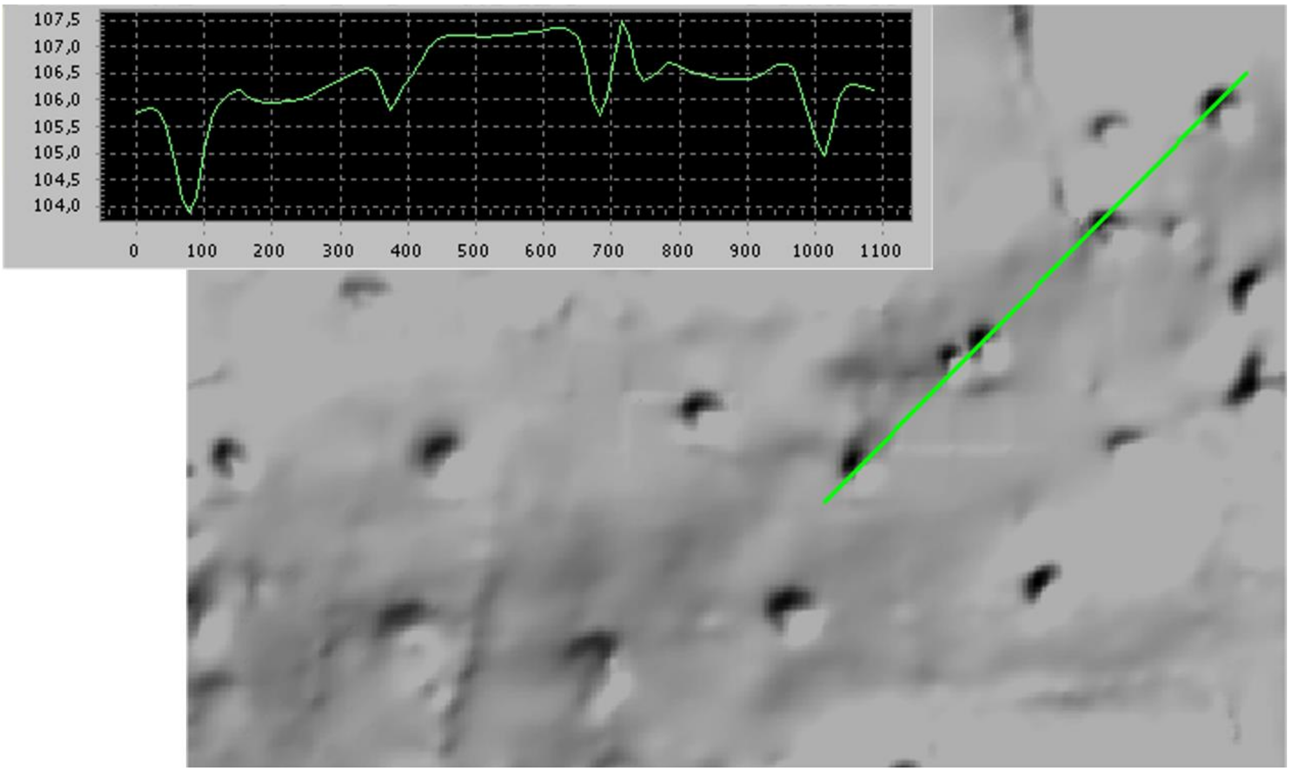

Fig. 5. Visualisation by relief shading of partly refilled brickearth pits, west of the Rhine (© Irmela Herzog and Renate Gerlach based on geodata provided by Geobasis NRW)

In many countries, the resolution of available elevation data increased considerably in the course of the last two decades partly due to new photogrammetric technologies (Structure from Motion, SfM) but mainly due to ALS adopted by many ordnance survey institutions. Initially, the ALS point density was only 1 measurement in 36 m² in forests (Zijverden and Laan, 2005), but nowadays about 19 ground points per m² can be achieved in such areas (Fig. 7: DEM 2015).

Zijverden and Laan (2005) introduced archaeological survey by ALS data visualisations to the Vienna conference in 2004. Their case study in the Netherlands used data that was made available in that year for the first time. They discuss the visualisation approach “hill-shading from different directions”. Simple hill-shading with varying parameters (vertical exaggeration, position and azimuth of the light) was also applied by Kosian (2008) at the CHNT conference in 2007. He discusses the detection and recording of field systems known as Celtic Fields (that in fact date from late Bronze Age, Iron Age into the early Roman era) in the Netherlands using elevation data with a grid size of 5 m provided by the Dutch ordnance survey agency. Remains of these field systems were also identified in the Rhineland where they are heavily eroded. Refined visualisation techniques are required to enhance the recognizability of these remains. Different visualisation techniques have been developed for ALS data and are implemented in free software (Hesse, 2010; Kokalj and Somrak, 2019; Zakšek et al., 2011). Two examples from the Rhineland are presented in the next chapter.

However, it is important to take the limits of ALS data for archaeological feature detection into account. Beex (2017) lists five issues on a poster presented at the CHNT21 conference:

- Most ALS data includes gaps that may obscure the presence of archaeological features;
- ALS data is often provided with automatic or semi-automatic classification of point data which is not perfect: archaeological features classified as (modern) built structures may be missing in the ground point set;
- the minimum size of features that can be detected depends on the ground point density (Nyquist limit, see above);
- the interpolation algorithms used for computing raster grids from the set of irregularly distributed ground points have limitations; and
- field validation of the results is required.

Recent applications of elevation data in the Rhineland

The situation in the Rhineland may appear like elevation data paradise for many colleagues: the ordnance survey institution Geobasis NRW provides open access ALS data with classified point data in laz format. Moreover, interpolated raster data with a cell size of 1 m is available, as well as four WMS layers providing grey and colour hill-shading of the 1 m DEM from two different directions. But there are also some drawbacks: the data is updated at regular intervals of about five years, and the old versions are no longer accessible online. The flight dates of all currently online available ALS data sets are provided in a separate metadata table, that should be downloaded when downloading the ALS data.

In Figure 6, two ALS data visualisations of a site in the forest near Lindlar-Scheel are shown. The aims of the ALS data analysis were: correctly delimiting and recording the site and its features as well as a nice presentation for the public. In Lindlar-Scheel, a ruin of the tower and some walls are still visible today. Therefore, the corresponding elevation points were classified as non-ground points in the ordnance survey data. To give the full picture, the points on the ruin and the walls had to be selected from the set of non-ground points, that also included a large number of points on trees. Thematic maps of the elevations assisted in the manual selection process. One of the most popular visualisation techniques is local relief model (Hesse, 2010) which highlights local elevations and depressions. Figure 6a shows an example of this approach combined with low-contrast hill-shading: depressions such as the ditch surrounding the castle are shown in green, elevated areas in yellow.

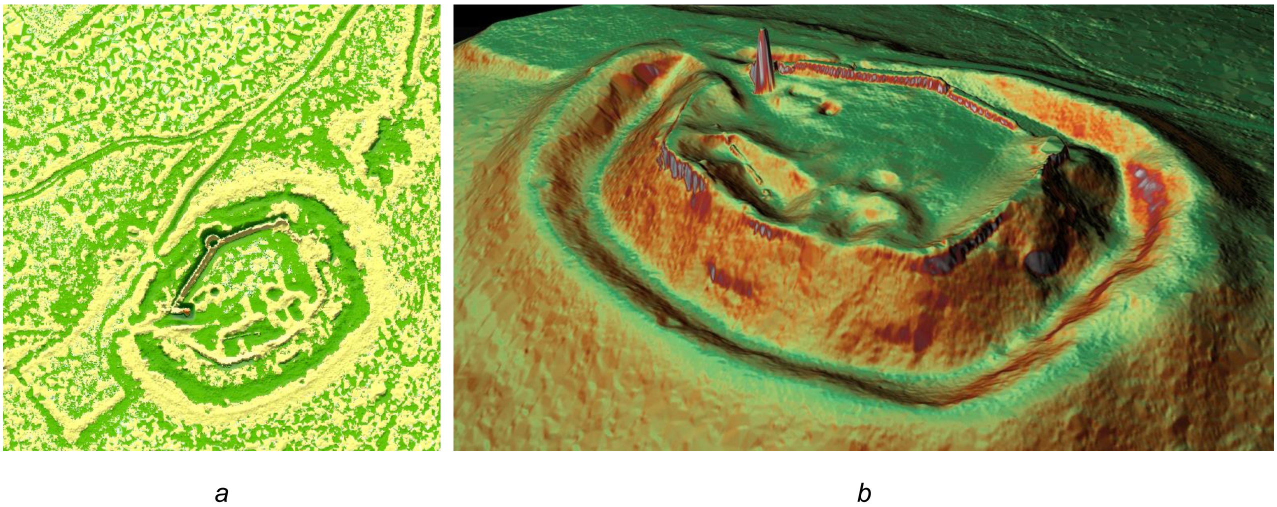

Fig. 6. Visualisations of ALS data depicting the remains of a castle known as Neuenberg a) local relief model; b) 3D view created by Planlauf/terrain (© Irmela Herzog based on data provided by Geobasis NRW)

The 3D visualisation in Figure 6b created by the Planlauf/terrain software benefits greatly from a colour scheme that depends on the slope values. Planlauf/terrain (https://planlaufterrain.com/) is a low-cost Windows application that uses gaming approaches for mesh decimation and thus allows virtual flights through the 3D landscape in real time that can be saved as mpeg files. The 3D environment provides a very intuitive approach for assessing the shape of a landscape feature. Films created by Planlauf/terrain are attractive assets for presenting a site mostly hidden by trees to the public.

A master thesis is currently in preparation with the aim of analysing prehistoric fortifications east of the Rhine by GIS methods. The preliminary list of sites consists of 41 entries, one of these is a likely earlier site at the Neuenburg location. High resolution (20 cm) DEMs have been derived from the irregularly spaced ALS data for relevant areas surrounding the sites. In a next step the sites were delimited as precisely as possible, and the remains of the ramparts were digitized. This allows comparing many features of the sites such as the area enclosed by the fortification, the current size of the ramparts, the slope of the surrounding area, and the shape. The aim is to derive a classification of the sites. A lower resolution (25 m) DEM is the basis of investigations into possibilities of communication between the fortifications either by signals or by routes. First results have already been published (Rung and Herzog, 2021).

Figure 7 illustrates the potential of ALS data sets from different years for monitoring sites. The ALS visualisations in the centre of Figure 7 use a colour gradient for elevation combined with hill-shading for visualising a protected site in Oberhausen. The late Medieval or early modern site consisted initially of ramparts and ditches.

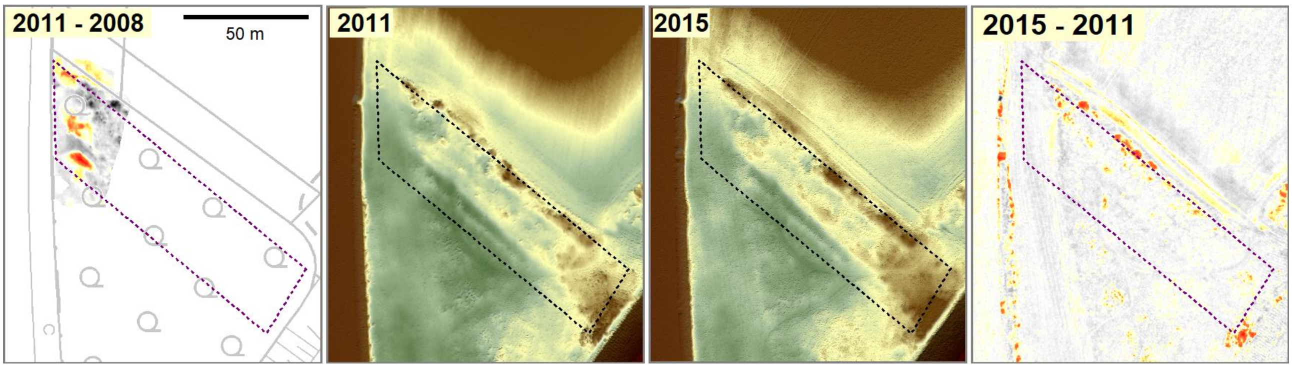

Fig. 7. The dotted line delimits a protected site, i.e., remains of a feature consisting of ramparts and ditches. The elevations of the western part of the site were surveyed manually in 2008 (739 measurements), the image on the left shows the difference to the DEM that was computed from ALS data recorded in February 2011. The red area highlights an elevation minus of about 40 cm. Hill-shading of the DEMs based on the 2011 and 2015 ALS data are depicted in the two centre images. The differences between these two DEMs are shown on the right. (© Irmela Herzog based on data provided by Geobasis NRW)

The DEM dated 2015 was downloaded in September 2019. The earlier DEM dated February, 2011 was delivered as a special favour to the Rhineland Commission for Archaeological Monuments and Sites in 2012, when this data was not yet free of charge. At that time, metadata was provided as well. After the CHNT25 conference, the elevation data recorded in March 2020 became available for download as well.

Figure 7 (left and right images) shows the results of subtracting two DEMs with the aim of identifying areas where the site was modified. On the left, the DEM generated from ordnance survey data recorded in 2011 is subtracted from the DEM based on manual altitude measurements performed in 2008 by an archaeological firm in advance of construction activities for a pipeline. Areas of material removal are highlighted in red, additions are shown in black. The resulting image shows that in the western part of the site, the ramparts were partly destroyed after the manual altitude measurements were taken in 2008.

Before computing the differences between the two ALS DEMs from 2011 and 2015, these DEMs had to be adjusted in elevation and position. Elevation data on the motorway—which is partly visible in the western part of the images in Figure 7—was used for assessing the difference in elevation. Artificial sections in north-south and east-west directions helped to assess possible displacements in these directions. The resulting image shows that in the time interval between 2011 and 2015, areas of removal are mainly located at or beyond the boundary of the site (Fig. 7, right). A more detailed analysis of the relief of the site presented in Figure 7 taking the elevation data recorded in March 2020 into account has been published (Herzog, 2021).

A similar approach for correcting horizontal and/or vertical displacement is discussed in the contribution by Herzog and Yépez (2016) presented at the CHNT20 conference. At this conference, another case study by Hesse (2016) introduced a systematic search for these offsets in ALS data in southern Germany.

Conclusions and Discussion

Elevation data provides the basis for most archaeological landscape analysis approaches and for detecting features in ALS data. In many countries it is no longer necessary to digitize contour maps, because high quality elevation data is freely available. In countries without such services, case studies in landscape archaeology often rely on satellite data with limited accuracy and resolution or on elevation points on digitized contour lines (Herzog and Yépez, 2016).

The main focus of this paper is on reusing elevation data recorded for non-archaeological purposes. An alternative is to instigate an aerial laser scanning project (e.g., Rom et al., 2020 at CHNT24) or in sparsely vegetated areas to use SfM. The potential and limits of SfM approaches for generating elevation data are summarised by Hesse (2016). In densely vegetated areas, processing ALS data for ground point identification is far from trivial as exemplified in a case study in Japan presented at CHNT24 (Herzog et al., 2021). Terrestrial laser scanning has also been used for recording elevation data as well as for recording excavation results. The contribution by Fichtmüller and Wollmann (2006) at the Vienna conference in 2005 was one of the first to discuss this technology.

When working with grid elevation data derived from irregularly spaced altitude measurements, the grid size of the raster DEM might be well below the largest gaps in the point cloud. Therefore, checking the Nyquist limit (Beex, 2004; 2017) with respect to DEM grid size might not produce a reliable result. Local large gaps in the point cloud may obscure archaeological features in this area. For creating a raster DEM from a set of irregularly distributed spot measurements or points on a contour line, an interpolation method must be chosen. The potential and limitations of different interpolation methods are discussed for instance in the contribution by Zijverden and Laan (2005) at the CHNT conference in 2004 and in text books on GIS applications in archaeology (Conolly and Lake, 2006, pp. 90–111; Wheatley and Gillings, 2002, pp. 114–119). Interpolation is also required if the raster DEM contains voids. This issue and other issues for instance with water bodies and coast lines were addressed by Kokalj et al. (2006) at the 10th conference in Vienna when presenting an application based on the freely available SRTM altitude data.

A substantial drawback of modern DEM data is the fact that the surface might have changed dramatically since the period considered. The work by Lechterbeck (2008) showed that contour lines on maps created more than 100 years ago might not provide reliable elevation data. Sometimes, surface reconstruction from bore hole data is applied (e.g., Golan, 2003; Zijverden and Laan, 2005). In this situation, the density of the bore holes determines the true resolution of the DEM. In the case study by Golan (2003), this is only about 1 bore hole per 1.3 hectare. As the average slope usually depends on the resolution of the DEM, this is vital knowledge for any slope-dependent analysis such as least-cost path or erosion computations.

Low resolution DEMs (grid size 10 to 100 m) are often applied in archaeological landscape analysis such as retrodictive modelling. This does not only reduce computational load but also reduces the impact of modern landscape modifications at a small scale by introducing some blur effect. It might turn out quite cumbersome to generate such a low resolution DEM from a DEM with a cell size of 1 m. For detecting large features such as the remains of bulk material extraction pits, medium resolution DEMs proved most effective in the Rhineland. In higher resolution DEMs small-scale features are more prominent and obscure larger structures.

Another tedious job is to search ALS visualisations of large areas with the aim of detecting archaeological features. Often, it is quite difficult to identify such features reliably in ALS data because they are partly destroyed or hidden by very dense vegetation. Therefore, two researchers may identify different features in the same study area. For a newcomer to this field, checking the feature candidates against known sites is a viable option for improving reliability. This is imitated by machine learning algorithms that are increasingly applied in recent years. Several approaches for selected archaeological feature types were presented at the CHNT24 conference (e.g., Kazimi et al., 2021). Machine learning applications based on DEMs and attributes derived thereof have been used before. For instance, Deravignone and Macci (2006) presented an Artificial Neural Network for PM of castle locations in the Tuscany region, Italy. They underline the computational load when dealing with high resolution DEMs and large study areas. Nowadays, more efficient and freely available implementations of machine learning algorithms as well as hardware improvements allow faster processing. Therefore, it is expected that machine learning applications will become more popular in many archaeological studies dealing with elevation data.

After acquiring the elevation data for a single site or landscape analysis, processing and visualisation are nearly always fun and provide not only nice pictures but also new insights. The future of CHNT will hopefully see the results of many nice applications of elevation data as well as the development of new technologies for analysing this data.

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Author Contributions

This paper mainly gives an overview over projects that were published previously. Details on the contributions to these projects can be found in the referenced publications.

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