Anthropogenic relief changes in a long-lasting lignite mining area (‘Ville’, Germany) derived from historic maps and digital elevation models

Felix Henselowsky1 | Julian Rölkens2 | Daniel Kelterbaum2 | Olaf Bubenzer1

1Institute of Geography and Heidelberg Centre for the Environment, Heidelberg University, Heidelberg, Germany
2Institute of Geography, University of Cologne, Cologne, Germany

Correspondence
Felix Henselowsky, Institute of Geography and Heidelberg Centre for the Environment, Heidelberg University, Im Neuenheimer Feld 438, Heidelberg, Germany.
Email: felix.henselowsky@uni-heidelberg.de

Abstract
Humans constitute one of the main geomorphological agents in modern times. As an example, post-mining regions represent a typical landscape of the Anthropocene. Strong relief modifications are particularly obvious with open pit mining. However, many existing mining areas are lacking detailed pre-mining information for the quantification of anthropogenic relief changes, which is a considerable challenge in regions with historic mining activities.

Here, the Ville (Rhenish lignite district, Germany) is used to quantify surface mining induced relief changes in one of the oldest and currently largest lignite districts in Europe. Historical maps from first geodetic mapping in 1893 enabled construction of a historic digital elevation model to quantify the relief changes in comparison to elevation data from 2000 and 2015. The vertical accuracy of the historic data is remarkably high, with relief differences < 2 m in areas not affected by mining. In total, 49.2% of the investigated area (184 km²) shows a relief deficit and 14.5% has positive relief differences. Absolute changes account for more than 80 m heightening (dumpsites of overburden) and lowering of the natural relief (pits). Besides these altitudinal changes, overall steeper slopes are significant for the new topography, but levelling exists likewise. The spatial variabilities are discussed in the context of the regional geology and the mining techniques.

Undoubtedly, such large-scale anthropogenic relief changes persist for a very long time and will last as a human legacy far into the future. Only the detailed reconstruction of the pre-mining relief offers the ability to clarify the dimension of humans as geomorphological agents and to understand landscape perception. Due to the fact that the impact of open pit mining has such a large vertical and horizontal extension, their consideration as part of anthropogeomorphology can significantly contribute to support future Critical Zone research in the Anthropocene.

KEYWORDS
Anthropocene, anthropogeomorphology, digital elevation model, historic maps, mining
INTRODUCTION

Geomorphological investigations can detect, quantify and monitor not only natural but also anthropogenic relief and landscape changes and can therefore contribute to the actual discussion about the “Anthropocene” (cf. Brown et al., 2017). In this context, the importance of geomorphology can be summed up in the statement of the primary concern of geomorphology should be with the investigation of processes and landform development, so providing the underpinning science for the study of this time of critical geological transition (Brown et al., 2017, p. 71). Today it is accepted, that humans, as geological and geomorphological agents are nowadays responsible for a higher amount of sediment and rock movement than the sum of all-natural processes (cf. Hooke, 2000; Price et al., 2011; Aguilar et al., 2020). Therefore, anthropogeomorphology the ‘study of the human role in creating landforms and modifying the operation of geomorphological processes’ (Goudie & Viles, 2016, p. 7) has subsequently emerged as a major field of research regarding any concerns about geomorphology within the Anthropocene. One of the very obvious and direct/intended anthropogenic landscapes, where humans have shaped the natural surface of the earth tremendously, are regions with surface mining activities. Very recently, the first disclosed global database detected more than 21,000 areas of active surface mining equivalent to an affected area of around 57,000 km² (Maus et al., 2020). Surface mining creates new negative landforms caused by excavation, new positive landforms due to dumpsites, and levelling landforms (cf. David, 2010; Mossa & James, 2013; Tarolli & Sofia, 2016). Other studies emphasize the importance of autonomous extraction of anthropogenic topographic signatures in mining landscapes in order to mitigate geomorphic hazards and sustain environmental planning (e.g., Chen et al., 2015). It represents a trend to use high-resolution digital elevation models (DEMs) to derive human topographic signatures in landscapes, where also ongoing acquisition of recurring high-resolution topographic data are used for active monitoring of surface changes and processes (Tarolli & Sofia, 2016; Tarolli et al., 2019). Given this modern ongoing data availability, historic quantification of anthropogenic changes over decades and centuries is limited due to missing historic DEMs. The implementation of historical maps however, facilitates the inclusion of an extended temporal dimension, if an accurate historical DEM can be computed based on them. This serves as a baseline for the computation of DEM of differences (DoD) (James et al., 2012). This is of particular importance in the investigation of anthropogenic relief changes in old mining regions. Here, the strong human impact was established in historic times. Some of the previous mining activities have been completed and subsequent land reclamation has been accomplished.

Recent research from the German working group on geomorphology demonstrates how historic DEMs can reconstruct the pre-Roman topography for the city of Aachen (Pröschel & Lehmkuhl, 2019), the palaeorelief of Leipzig from the year 1050 (Grimm & Heinrich, 2019) or the pre-modern terrain for the Charlemagne’s canal construction site in Bavaria (Schmidt et al., 2018). In these examples, data from archaeological excavations and geological drillings have been used. Harnischmacher and Zepp (2014) display the impact of anthropogenic induced subsidence due to underground mining along the Ruhr District based on elevation data from first geodetic mapping represented on historical maps from the Prussians (Preußische Neuaufnahme). However, the analysis of area-wide anthropogenic relief changes on the basis of historical topographic maps of large surface mining areas, which differ obviously from that of underground mining areas, does not presently exist.

Following this context, the study at hand aims to detect and quantify human induced relief changes in the Ville mountain range, a tectonic horst structure in the Cologne-Aachen area, Germany (southern Lower Rhine Embayment). Here, substantial anthropogenic relief changes, not only with regard to extensive open-pit lignite mining but also with regard to reclamation and recultivation, are evident over the past 200 years. Since the Lower Rhine Embayment comprises fertile loess soils, the former mining area received very early attention from international specialists for the process of reclamation (e.g., Elkins, 1953; Nephew, 1972).

Issues with regard to resulting landscape changes focusing on relief differences are: (i) in which dimension changed the relief under the influence of mining, (ii) which new relief forms were created, and (iii) what is the relationship between new landforms and land use? Altogether, this can be achieved by a detailed geomorphological mapping created by an adequate data background in spatial and temporal scales for the period of interest.

STUDY AREA

The Rhenish mining area extends over an area of 2500 km² (Dvorschak & Rose, 2014). It represents the largest lignite district in Europe and the main focus of lignite mining in Germany (95 Mt production/a), in addition to the Lusatian mining area in eastern Germany (62 Mt production/a) and the central German mining area (19.3 Mt production/a) (Alves Dias et al., 2018). Together with Poland, Bulgaria and Romania, Germany has also the largest lignite mines in the European Union, predominantly operating as open-pits. In total, the three lignite regions in Germany contain more than 10% of the remaining global commercially exploitable brown coal deposits (Meschede & Warr, 2019) and Germany is currently the second largest coal producer in the world, following China.

In this context, the Rhenish mining area within the southern Lower Rhine Embayment in the Cologne-Aachen region (Figure 1) provides an extraordinary example, where humans have produced substantial relief changes due to open lignite mining. Today, exploration is still ongoing in three large open pit mines (Hambach, Garzweiler and Inden, cf. Figure 1). The area under investigation is located between the oldest mining pits in the south of the Ville horst and the former lignite mine of Bergheim, where recultivation measures were completed in 2012.

2.1 Tectonic setting and actual land use

The southern Lower Rhine Embayment is part of the European Cenozoic rift system, where tectonic subsidence occurred, since the Oligocene and lignite deposits originate from Miocene peat deposits. Two major seams (main- and upper-seam) have thicknesses between 10 m and up to 40 m respectively and exist next
to various thinner peat deposits [cf. Hager (1993) for the origin of lignite deposits in the lower Rhine region]. The ongoing tectonic activity of the Lower Rhine Bay has divided the basin into different separate blocks along the main trend lines from northwest to southeast. The depth of the lignite deposits below the present surface is dependent on the different tectonic subsidence and erosion/deposition of Pliocene and Quaternary, mainly unconsolidated sediments (cf. Ahorner, 1962). Apart from minor Late Pleistocene loess deposits, the Middle Pleistocene upper terrace of the Rhine River represents the natural surface of the Ville horst with varying thicknesses (Boenigk & Frechen, 2006). In the southern part of the Ville horst, the lignite occurs near the surface and subducts towards the north, partly to more than 450 m below the surface (up to about 370 m below sea level).

Palaeoseismology and modern-day seismicity verify active tectonics in the Lower Rhine Embayment in the Holocene, including historic times (compare latest summary in Hürtgen et al., 2020). For example, a strong earthquake (ML 6.1) occurred in Düren in 1756 (Ahorner, 1962), located approximately 20 km west of the Ville horst. Active faults are also situated just 5 km south of study area (Kübler et al., 2017). In addition, recent movements detected by geodetic measurements point to mining-induced subsidence of up to 2 cm/yr due to groundwater extraction, but also due to ongoing extension of the rift system with a few millimetres per year within the Lower Rhine Embayment (Campbell et al., 2016). Thus, the complex tectonic setting is not only responsible for the spatial distribution of the lignite seams, but also an important impact factor, which could affect recent and future anthropogenic landforms.

As the study area was chosen to demonstrate changes between the natural landscape and recultivated post-mining landscape, its current land use does not indicate the landscape history at first glance. Today, most of the study area is forest (61.8 km² or 33.6%), followed by agriculture (56.9 km² or 30.9%) and residential areas (25.8 km² or 14%). An active mining area (0.9 km²) relates only to ongoing quartz-sand mining (Geobasis NRW, 2019).

2.2 Mining history and excavation techniques at a glance

The presence of lignite may have been known since Roman times, when Tacitus describes burning soils in AD 59 (Kaever, 2004). First documented industrial mining activities occurred in the late 19th century with the introduction of industrial lignite briquettes (Brunotte et al., 1994). Mining began in the southern part of the Ville, where the Tertiary lignite layers were exposed near the surface. This resulted in the excavation of very small and shallow mines and only small amounts (< 10 m) of overburden material (sands and gravels) had to be removed. Here, no fertile soils were destroyed and only woodland was affected by mining (Dickmann, 2011). Thus, there were almost no land-use conflicts at this ‘island of infertility’ (Elkins, 1953, p. 132).

The first General Mining Act existed in 1865 and had only very few statements on recultivation and reclamation of mining areas (Dickmann, 2011). With regard to the tectonically submerging lignite layers towards the north, technical developments in the first half of the 20th century allowed deeper excavation and the further expansion of mines. For the purposes of land reclamation, forestry and farming recultivation, the growing amount of overburden from unconsolidated sediment masses, were to be deposited in mined out pits (state mining authorities in 1929, cited from Dickmann, 2011). Since the 1950s, the introduction of the first bucket-wheel-excavator opened up pits with operating depths > 200 m below the natural surface. These were the largest open pit mines in the world at that time (Bauer, 1971). Increased mine depth resulted in increased overburden material which in turn led to too little deposit capacity in the shallow mines. The material was consequently dumped at heap sites. One example was Glessen. It was built between 1955 and 1970 and has a height of 80 m above the natural landscape and has a storage capacity volume of 170 million m³ (Brunotte et al., 1994). Hence, the thick layers of overburden, unconsolidated sediments, which prevent underground mining are the reason that large open pits are typical for the Rhenish lignite district. The highest ratio between overburden...
sediments (in m$^3$) and lignite (in tonnes) is about 6:1 for the open pit of Hambach. Mining is only possible due to the massive technological developments of large bucket wheel excavators. (Dworschak & Rose, 2014). In conclusion, the region experienced massive anthropogenic relief changes.

3 | METHODS AND DATA

In January 2017, the government of North-Rhine Westphalia launched the new established database for free available geodata, as part of the movement towards an open government portal (https://open.nrw/). The allocation of a high-resolution DEM with 1 m pixel resolution, based on airborne LiDAR (light detection and ranging) with average point density of 4 to 10 pts/m$^2$, horizontal accuracy of ±30 cm, and vertical accuracy of ±20 cm (Geobasis NRW, 2019), provides one of the big advances to study the recent relief. In addition, geodetic historic maps can provide insights into the former relief and land use. For the study at hand, firstly a computation of a historic DEM based on elevation data from contour lines of the geodetic topographic maps of the ‘Preußische Neuaufnahme’ with a scale of 1:25,000 was conducted. The methodology follows the approach of so-called PalaeoMaps (Willmes et al., 2017), which highlights the conversion of spatial data of non-digital data (e.g., analogue maps, tables, figures, etc.) into digital geographic information system (GIS) data for spatial analysis and which reflects the high importance of historical reconstructions in the course of global change studies (James et al., 2012). The original data in the study area have been mapped in the year 1893, providing the background for a comparison with the topography in 2000 based on Shuttle Radar Topography Mission (SRTM)-data, and with the latest high-resolution LiDAR DEM from 2015 with 1 m pixel resolution. Qualitative comparisons, although without area-wide geodetic measurements, can extend up to the time of 1803 to 1820, when the first detailed mapping of the Rhineland was done (Figure 2). Finally, the detected anthropogenic landforms and relief differences between and after mining are compared with the recent (2015) landscape model (DLM 50) of the area.

All input data are based on free available geodata from the federal state of North-Rhine Westphalia, respectively the US Geological Survey (USGS) data repository (SRTM). The current and historic topographic maps are available online. All input data can be used without restrictions or conditions based on the Data licence Germany – Zero – Version 2.0. Following a strict open science approach, the resulting DEM is subsequently published as an open data set and available via https://doi.org/10.11588/data/LSG8TN

3.1 | Computation of the historic DEM from 1893

The historic DEM (1893_DEM) is created based on the digitized contour lines of the Preußische Neuaufnahme, in which the digitized contour lines have an interval of 20, 10 and 5 m, with single intermediate contours of 2.5 and 1.25 m. The entire study area has a size of 184 km$^2$. The cumulative length of all digitized contours is 2030 km and a total of 61,564 points are derived from the vertices of digitized contours. This led to an average point density of 334 pts/km$^2$.

The height reference for the historic topographic maps is the normal Amsterdam Peil. The vertical reference datum of the 2015_DEM based on the LiDAR derived DEM of North Rhine-Westphalia is the DHHN2016 height (EPSG 7837). This geodetic datum is also set with regard to the Normal Amsterdam Peil (Feldmann-Westendorff et al., 2016) and the vertical differences following the transformation from the historic and modern reference system are neglectable for the observation scale (metres) from this study, also shown by comparable approaches from Harnischmacher and Zepp (2014). This allows a simple calculation of relief differences between the 1893_DEM and the 2015_DEM. The computation of the 1893_DEM as gridded DEM has to account for the given characteristics of the input data. These are, in the study at hand, irregular distributed points, with maximum point density in regions with the highest relief variability due to more

![Figure 2](Color figure can be viewed at wileyonlinelibrary.com)
dense contour lines. Two parameters need to be set before computation: appropriate pixel size of the DEM and the interpolation method. Different approaches for the use of an appropriate pixel size are given in Table 1.

As the input data itself have a fixed spatial resolution given on the map scale (here 1:25,000), a first approximation for an appropriate pixel size can be calculated from a cartographic point of view. Tobler (1987) suggests a maximum spatial resolution with the division of the denominator of the map by 1000 and a minimum spatial resolution half of this amount, which lead to a pixel size between 12.5 m to 25 m for our input data. Hengl (2006) sees the coarsest grid resolution based on cartographic concepts in relation to the minimum legible delineation as scale number (SN) × 0.0025, which results in a maximal spatial grid resolution for the Preußische Neuaufnahme of 62.5 m. The finest spatial resolution is depending on the maximum location accuracy and results in 2.5 m pixel resolution for a map scale of 1:25,000 (SN × 0.0001). The minimum spatial resolution is calculated with pixel size = total size of study area/(2 × total cumulative length of digitized contours) (Hengl, 2006). In this case, the final DEM needs a minimum pixel size of 45 m (p = 184 km² / (2 × 2030 km)). This is in accordance with the average distance from any point in the study area to its next contour line, which is 43.3 m. The most distant unknown point is 426 m away from its next contour line. Hence, a minimum pixel resolution of 43.3 m is needed in average to display height differences between two contours accurately. The mean distance from an unknown point to its next contour line is within the 20% of most dense region of contours, thus the area of most relief changes per area is 13.1 m and represents the maximal pixel resolution with regard to contour density. A stricter approach based on the derivation of the 5% probability smallest width of contours (Hengl, 2006) is avoided as the internal error of the input data itself can have an impact on this very strict approach. Thus, the region with 20% of the densest contours is a more reliable threshold for this study. Ultimately, a pixel size of 30 m was chosen for the calculation of the 1893 DEM, which fulfills all above criteria.

The second important parameter for the computation of the 1893 DEM is the interpolation method. Here, a Thin Plate Spline function (Donato & Belongie, 2002) has been used for the interpolation of the historic DEM using SAGA GIS Software (Conrad et al., 2015). Input parameters were set to a maximum search distance of 450 m (maximal distance to an unknown point), local search range and a minimum of 16 points for interpolation. This accounts for the prevention of over-shooting and over-smoothing as a possible problem with spline interpolation (Hengl & Evans, 2009).

The final quantitative comparison of relief changes between the situation in 1893 and 2015 is based on the height differences with the aggregate version (natural neighbour) of the initial 1 m pixel resolution of the 2015 DEM to the same extent and pixel size of the historic DEM. Slope values for the historic DEM are classified according to the low land slope classes [geomorphological mapping after Leser and Stäblein (1975)], drainage channels starting with a minimum Strahler Order of 5 and catchment areas were calculated based on the sink filled DEM.

4 | RESULTS

The results of this study are divided in three sections. Firstly, the historic DEM from 1893 is presented with regard to the natural landscape and geomorphological setting of the Ville in combination with the first area wide mapping of Tranchot (1803–1820). Secondly, the relief changes between 1893, 2000 and 2015 are shown, and lastly the current land use is presented with regard to the previous relief changes and present topography.

4.1 | The historic digital elevation model from 1893

The historic maps are able to show the landscape of the Ville before any lignite mining. The first mapping of the area between 1803 and 1820 (Figure 2A) illustrates the topography of the Ville in shaded relief structures (Lehmann’s slope hachures) but without quantitative geodetic height information. No larger anthropogenic landforms are detectable on these maps although small-scale exploration pits already exist (not only lignite, but mostly sand and gravel pits). The same situation exists for the ‘Uraufnahme’, mapped between 1836 and 1850. However, here the quantity of small-scale mining pits is enlarged.

The topography for the computed historic DEM from 1893 (Figure 2B) ranges between 62 to 159 m above sea level (a.s.l.), with a general trend of higher elevations in the southern part and a descending trend towards the north. The general morphological character of the landscape is comparable to the first maps of Tranchot. The western slope of the Ville hogback follows a main tectonic ‘Erft fault line’ and has therefore a steeper gradient in comparison to its eastern slope, where a distinct fault line is missing and which was formed by fluvial erosion of the ancient Rhine River.

| Table 1 | Summary of different approaches for the calculation of a suitable pixel size for digital elevation model (DEM) derived from analogue topographic maps |
|---------|---------------------------------|-----------------|-----------------|-----------------|
| Coarsest pixel resolution | Finest pixel resolution | Source | Transfer to this study |
| Cartographic concepts | (denominator of map/1000) | (denominator of map/1000)/2 | Tobler, 1987 | 25–12.5 m |
| Minimum legible delineation: scale number * 0.00025 | Maximum location accuracy: scale number * 0.0001 | Hengl, 2006 | 62.5–2.5 m |
| Contour line based | Study area/(2 * cumulative length of digitized contours) | 5% probability smallest width of contours | Hengl, 2006 | < 45 m |
| Contour line based | Mean distance to contour line | Mean distance of contours in 20% of the most dense region | This study | 43.3–13.1 m |
Very noticeable is the visibility of tectonic displacements within the historic DEM. Several fault lines are obvious on the Ville surface itself, which are not clearly visible in the actual topography. The most enlarged fault is the ‘Frechener fault’ in the north-western part of the Ville. It follows the 125 m isohypse and represents the highest tectonic level of the central part of the Ville.

The largest calculated catchment counts to 15.7 km² (Figure 2C) and drains south of the Frechener fault towards the west into the Erft River. Several smaller catchments in the central part of the eastern Ville, which marks its eastern border and the transition from the upper to the middle Rhine terraces, drain towards northeast.

4.2 | Relief differences 1893–2000–2015

The natural topography of the Ville in 1893 varied between 62 and 159 m a.s.l., whereas the recent topography has heights between 63 and 207 m a.s.l., which extends the range of height differences and fabricates a more variable relief. In between, the situation in February 2000 (SRTM-data acquisition), shows the ongoing mining activity at the open pit of Bergheim with a minimal level of 96 m below sea level at this time.

The lignite-free region northeast of the Frechener fault as the highest tectonic level of the middle part of the Ville horst represents the largest non-mining area for comparisons. Here, the main seam was eroded during Tertiary and Quaternary periods and the deposits of the younger upper main terrace overlie Oligocene marine quartz sands. In addition, the heap site ‘Glessener Height’ was generated here. The Oligocene quartz sands are still being mined in an open-cast mine. Therefore, the associated negative relief form is not related to lignite mining.

Only minor areas with no relief changes exist at the top of the Ville horst. Net relief changes between 1893 and 2015 (Figure 3A) are divided into 49.2% of the area with changes > −2 m, 36.2% with relief changes between −2 to 2 m, and 14.5% with relief changes > 2 m. Maximum positive relief changes are up to 80 m (’Glessener Height’).

Further dumpsites are visible (Fischbach Height, Abtsbusch, Röttgen Height and Wilhelms Height). Most of the unchanged areas are on the foot of the eastern and western slope of the Ville horst.

The differences between 1893 and 2000 (Figure 3B) show in general already the same pattern as the final situation in 2015, as most of the affected area at the Ville has already been recultivated during that time. Thus, the large differences of mostly negative landforms in the southern part and the new positive landforms in the northern part are comparable. However, the unchanged areas at the western and eastern edge of the Ville horst, but also the lignite-free region north of the Frechener fault, show more noisy differences in the range of −5 to 5 m.

Three larger areas exhibit distinct positive relief differences between 2000 and 2015 (Figure 3C). Changes in the open pit of Bergheim, which was still active in 2000, have positive values of up to 184 m due to infilling of the former pit. Positive changes are also visible for the ongoing upfilling of the former pit of Frechen, which was only finished in 2003, showing a relief difference of +65 m from 2000 to 2015. Further dumping is present in the southern part with a still ongoing waste disposal site.

4.3 | Slope differences 1893–2000–2015

The slope classification for the natural topography of the Ville in 1893 has its maximum with 43.7% of the area ranging between > 0.5° and 2° (Table 2). Only 2.4% shows values in the classes of 7° to 15°. Slopes with values above 15° are absent.

The spatial distribution of slope values (Figure 4A) displays the differences between the eastern and western part of the Ville horst. Whereas the eastern slopes show a more varying development of small streams and backwards incision, the western slopes display the more distinct boundary along the main Erft fault. On top of the Ville horst, slope values are mostly below 4°, apart from some higher
values, for example along the Frechener fault. A considerable increase is observed for the situation in 2000 and 2015. Figure 4(B,C). Especially the slopes of the dumpsites (central part), the active open pit of Bergheim (northwestern part), the quartz mining area of Frechen, and the irregular topography in the southern part of the Ville horst show steeper slopes. However, apart from the minor relief differences between 2000 and 2015, which changes the slope distribution, the actual anthropogenic and natural landforms are more distinguished in the data from 2015. The overall increase in slope is also apparent with 12.4% (2000) and 9.9% (2015) of values above $7^\circ/C14$, which is comparable high for a natural low land landscape (cf. Leser & Stäblein, 1975). The distinct slopes at the western edge of the Ville, which mark the natural tectonic boundary towards the west, are almost totally dissolved in the post-mining landscape. Only the north-eastern and south-eastern slopes trace the natural character of the morphometry. Slope classification for the full resolution of the original DEM from 2015 with 1 m pixel resolution has the general trend to reduce small values and an overall increase in higher values. Noticeable is an increase of values greater than $15^\circ/C14$ (7.8%) in comparison to the general decrease of values for the classes between $0.5^\circ$ and $15^\circ$.

### 5 | DISCUSSION

The discussion of the presented results follows an examination about the technical and methodological computation of the historic DEM, the derivation of the new anthropogenic landforms and the overall benefit of such investigations with regard to the input of anthropogeomorphological studies in the discussion about the Anthropocene.

#### 5.1 | Quality and comparability of the datasets

The accurate computation of the historic DEM is crucial for the quantification of the anthropogenic topographic impacts in the area under investigation. The used spline algorithm avoids a linear interpolation (Reuter et al., 2009). Systematic errors are often represented by terraces, a common feature in interpolated DEMs based on contour data (Reuter et al., 2009). The high correlation, over the total study area, between the input heights (digitized from the contours) and computed heights indicated with the very small root mean square error (< 1 m between observed and predicted height) shows that the spline algorithm did not produce large over-shooting and interpolation errors with the given input data parameters. However, no information exists regarding the vertical accuracy of the mapped contour lines, as the height information itself is only represented as an absolute value on the analogue maps without metadata. This is a common problem for the use of contours from analogue maps and other studies, for example Harnischmacher and Zepp (2010) account for this with a nugget variation of zero in their interpolation of the historic DEM using the kriging interpolation. This accounts for the missing vertical error assessment of the input data. A reference area in the north-eastern part of the Ville horst, where no mining or other larger human activities took place, constitutes for the accuracy assessment of the historic DEM.

Table 2: Slope classes according to low land classification of Leser and Stäblein (1975) for the digital elevation models (DEMs) from 1893, 2000 and 2015

| Slope classification | 0°–0.5° | > 0.5°–2° | > 2°–4° | > 4°–7° | > 7°–11° | > 11°–15° | > 15° |
|----------------------|---------|-----------|--------|--------|--------|--------|-------|
| 30 m pixel 1893      | 22.3    | 43.7      | 22.0   | 9.5    | 2.1    | 0.3    | 0.0   |
| 2000                | 7.5     | 34.9      | 29.3   | 15.9   | 7.0    | 3.0    | 2.4   |
| 2015                | 17.5    | 42.5      | 19.3   | 10.9   | 5.4    | 2.5    | 2.0   |
| 1 m pixel 2015       | 9.2     | 40.2      | 23.0   | 11.5   | 5.4    | 3.0    | 7.8   |
DEM in comparison to the modern DEM. Here, the height differences between 1893 and 2015 have a mean difference of \(-0.14 m\) with a standard deviation of \(1.49 m\) and a linear correlation of \(R^2 = 0.9595\). Hence, the threshold of \(\pm 2 m\) is sufficient to identify areas with no (respectively smaller than \(\pm 2 m\)) relief changes between 1893 and 2015, which also represents a sufficient scale to detect mining induced changes.

Although further small-scaled natural relief changes apart from mining activities are plausible between 1893 and 2015, for example due to long-term soil erosion, they cannot be integrated into the computation for the area in total and are also insignificant for the test site of the non-disturbed relief. Firstly, their spatial variability is too complex and demands the integration of subsurface information. Secondly, although linear soil erosion features in the magnitude of several metres do exist (cf. Fischer, 2010), they were generating over a much longer timescale since the Neolithic. Thus, changes between 1893 and 2015 are comparably small and former long-term relief changes are already incorporated in the topographic information from 1893.

The exemplified visible tectonic faults lines serve as additional validation for the vertical accuracy of the historic DEM within the range of \(\pm 2 m\). Ahornner (1962) describes the surface offset, based on field mapping at that time, at the Louise fault with \(8-10 m\), which is in the same magnitude as the historic DEM indicates for this fault. This proves the comparable high vertical accuracy of the data.

Overall, the data accuracy of the historic DEM from this study is comparable to the very few other studies, which have used the Prussian topographic maps previously with regard to geodetic information. Our threshold is comparable to the accuracy of the historic DEM in the Ruhr District, where 51% of data are affected with an error between 1 and 2 m, 48% below 1 m and only 1.3% with an error above 2 m (Harnischmacher & Zepp, 2014). Similarly, the historic DEM based on the Prussian topographic maps (here from 1883) for the Upper Silesian Coal mining area has a maximum altitude error of \(\pm 0.45 m\) (Dullas, 2016). Whereas these studies used the Prussian topographic maps mainly for the reconstruction of a historic DEM to map relief subsidence due to underground coal mining, another example based on these maps is the reconstruction of coastline changes, where the maps have a horizontal average accuracy of 5 m (Deng et al., 2017).

Apart from the approximation to get the right pixel size with the coarsest and finest legible raster resolution for the given input data, ‘No absolute ideal pixel size exists, that is for sure’ (Heng, 2006, p. 1297). In general, varying density of points and a generalization of topography challenge the interpolation of a gridded DEM derived from digitized contours (Reuter et al., 2009). It is important to note, that some software like ArcGIS sets by default a spatial resolution for the resulting interpolation of subdivision of the shortest size of the study area by 250. For our study area, this would lead to a pixel resolution of 75.4 m, which is by far too coarse for the scale and spatial resolution of the input data. Hence, the detailed description of the chosen pixel size for the historic DEM is mandatory. The used pixel size of 30 m for the historic DEM is able to display the main natural morphological character of the region with comparison to the oldest overall mapping of the area, based on the morphometric characterization of Lehmann hachure-slopes as visualization of topography on the maps from 1803 to 1820. This is a primary systematic method of relief visualization on historic topographic maps, but lacks geodetic information (Zentai, 2018). The comparisons of the computed historic DEM with the overlay of the Preußische Neuaufnahme provides in addition, a final visual assessment for the consistency of the derived historic DEM and shows that the spacing of historic contour lines and the spatial resolution are within the same scale.

5.2 Limitation of the dataset

Our data are unable to quantify all topographic changes that occurred during the periods between the three considered points in time. This limits the overall quantification of the moved lignite and sedimentary rocks. In addition, it is possible that nowadays positive landforms have been mined before dumping. The Fischbach Höhe west of the Frechen fault and the Glessener Height were constructed during the 1970s, but were previously mined until 1955. Thus, the detection of areas affected by both excavation and dumping is not possible and only the sum of all topographic differences between the pre- and post-mining landscape is ascertainable. Therefore, apart from the vertical uncertainty in the accuracy range of \(\pm 2 m\), usually the actual amount of displaced material is higher than the final differences.

Apart from the larger relief differences between 2000 and 2015 with the ongoing backfilling of Bergeheim (northern part) and Frechen (central part), as well as the waste disposal site in the southern part, all other visible relief differences between 2000 to 2015 are due to the accuracy of the SRTM-DEM. The accuracy of the SRTM-data in Eurasia is on average \(\pm 6.2 m\) for the absolute height (Rodriguez et al., 2006), which is comparable to the accuracy assessment of the SRTM-data in comparison to the German DEM50 in a study area southeast of Cologne (Bolten & Bubenzer, 2006). In comparison, the LiDAR data have a vertical accuracy of \(\pm 20 cm\) (Geobasis NRW, 2019). Whereas the LiDAR data from 2015 are able to dissolve tree canopy heights, the SRTM-data are more affected by errors in forested areas, and these elevation data represent rather a surface model than a terrain model. The majority of negative relief changes (67.4%) between 2000 and 2015 in the southern and northern part of the study area are located in current forested areas (cf. Figure 3 at Königsdorfer Forst and Ville Forst). Thus, negative changes with a relief deficit > 2 m are caused by technical disadvantages of the SRTM-data in contrast to effective relief changes at this magnitude. Positive relief changes are also visible in regions with current higher slopes, which has in addition a negative impact to the accuracy of the SRTM-data. It is obvious that the tested high accuracy of the historic DEM, which has been calculated from geodetic topographical maps, is better than the computed SRTM-DEM. However, the frequently used SRTM data set is being increasingly replaced by more advanced data sets. (e.g., the TandemX-WorldDEM, ESA) The acquisition of the SRTM data in only a few weeks in 2020 produced a relatively precise snapshot for the mapping of anthropogenic relief changes and DoDs. Moreover, the magnitude of relief changes due to large-scale surface mining with depths > 200 m depth, is high enough to detect the ongoing backfilling between 2000 and 2015. Thus, for comparable investigations, the SRTM data set will eventually have a revival in anthropogeomorphology. In addition, the worldwide data acquisition of the TanDEM-X mission between 2017 and 2019 will soon result in a global ‘DEM of change’ in comparison to the first mapping period of TanDEM-X between 2010 and 2015 (https://tandemx-science.dlr.de/).
5.3 | New anthropogenic landforms

Apart from the absolute relief differences, the character of the post-mining topography has significantly changed the landscape setting. This is remarkably visible in the direct comparison of the topography between 1893 and 2015 (Figure 5). The anthropogenic relief is much more pronounced and more heterogeneous than the original natural relief and constitutes a typical human topographic signature for relief alternation (Tarolli & Sofia, 2016).

A central question is if the anthropogenic topography has a distinct morphometric fingerprint (cf. Tarolli & Sofia, 2016). The total increase in high slope classes of the investigated area can be explained due to the generation of artificial dumpsites with steep slopes. The increase in moderate slopes between $2^\circ$ and $7^\circ$ for the situation in the year 2000 at the top of the Ville apart from the natural western Ville slope are caused by the noisy SRTM-data. The high-resolution data from 2015 show remarkable artificial slopes in areas of recultivation with new positive and negative landforms. Here, higher slope classes with 4.5% of slopes $> 11^\circ$ in comparison to 0.3% of slopes $> 11^\circ$ for the year 1893 can be regarded as a morphometric index for an anthropogenic changed relief, as the natural topography for this kind of landscape in the middle lowlands do not have such a wide distribution of slope ranges (e.g., Leser & Stäblein, 1975). The increase of higher slope classes as an effect of the DEM with a higher resolution can be excluded, because the slope classes for 2015 are also calculated based on the aggregated DEM with 30 m pixel resolution. The initial spatial resolution of 1 m shows 10.8% of the total area with slopes higher than $11^\circ$. It is remarkable that the general decrease of slope from its maximum between $> 0.5^\circ$ and $2^\circ$ up to $>11^\circ - 15^\circ$ is interrupted by an increase of 7.8% with slopes $> 15^\circ$ (cf. Table 2). Thus, both slope classes derived from the aggregated 30 m and the initial 1 m DEM for 2015 shows the typical anthropogenic alternation of specific slope values of artificial topography in the slope distribution (Tarolli & Sofia, 2016). However, apart from the general anthropogenic increase in higher slope values in total, mainly caused by the large dumpsites in the northern part of the Ville, as well as steep slopes along the edges of the anthropogenic lakes in the southern part, some specific regions are also affected by a decrease in slope and a more gentle relief. This relates to specific locations of previous mines, for example at the formerly western edge of the Ville with the open pit of Frechen, where backfilling has levelled the topography. Here, the lowering of topography has a similar anthropogenic signature as mountaintop mining (Ross et al., 2016). In addition, reclamation for new agricultural landscapes has also levelled the topography and produced a more gentle relief with only very weak inclination for surface runoff (Dworschak & Rose, 2014).

Overall, the spatial differences and distribution of total relief changes return to the geological structure of the Ville and the technological mining history from small-scale surface mining in the south without any larger pit sites, to large-scale deep mines in the central and northern part. The latter will be subsequently discussed in more detail.

5.3.1 | The southern part of the Ville

The first open pits for lignite mining were mapped in 1893 (Preußische Neuaufnahme) in the southern part of the study area. However, the limited extent of these pits in their initial status did not significantly change the topography and there are no artificial dumpsites in the surrounding of these pits, due to the thin sedimentary cover above the former lignite layers. Such mining activities took place in times with no detailed regulations for post-mining reclamation and recultivation. For example, narrow linear ‘valleys’ represents former railroads for the lignite transport, which were excavated subsequently. The resulting small-structured relief was unplanned and the small pits were scarcely recultivated or refilled. This resulted in the formation of various lakes (‘Ville lakes’). However, in comparison to the pre-mining landscape, the heterogeneous and only partly experimental recultivation of the southern part during the first reclamation phase (1920–1945) resulted in a higher ecological diversity with new biotopes, plant and animal communities (Bauer, 1971).

![Figure 5](https://wileyonlinelibrary.com)
Given the fact, that this region was formerly seen as poor-quality land with regards to agriculture (Elkins, 1953), the enhanced ecological diversity and the post-mining land use has provided local recreation areas for the cities of Cologne and Bonn with forests and small bathing lakes. They are examples for the positive potential of post-mining landscapes (Wirth et al., 2017). To our knowledge, this region constitutes the earliest examples, where already during the 1950s the conscious transformation of a post-mining landscape as a recreation area for the local inhabitants was described (Elkins, 1953) and executed.

The generally lowering of the relief, without any larger anthropogenic landforms and only small-scaled more heterogeneous landforms, becomes clear in the detailed comparison between 1893 and 2015 (Figure 6).

5.3.2 | The central and northern part of the Ville horst

The central and northern part of the Ville horst is characterized by mines of greater depth and dimension. Here, in contrast to the sparsely populated infertile southern part, farmland and villages with several thousands of inhabitants had to be relocated (Dickmann, 2011). This resulted in a stronger focus on planning legislation, which also affected the created anthropogenic relief. The location of the Glessener Height is the largest dumpsite in the investigated area was planned to be built as high as possible so as to minimize the amount of land required. This resulted in the very steep, forested slopes as well as the flat top designated as agricultural fields (Figure 7A). As there were no existing large-scale open pits before, in which to deposit the thick overburden sediments from the first deep mines in the northern part of the study area, this type of landscape and relief are typical for the reclamation period of the 1950s and 1960s (cf. Brunotte et al., 1994).

A comparison between 1893 and 2015 indicates that the natural, tectonic induced steep slope of the western edge of the Ville has totally disappeared in some areas. Here, the new topography at the previously open pit of Frechen (Figure 7B) is an example of an extreme relief alteration with a backfilling of the previous deep mine only up to the natural level of the Erft basin. This is comparable to mountaintop mining, where the previous heterogeneous relief is levelled and anthropogenic topography has a gentler slope in comparison to the natural relief (e.g. Ross et al., 2016). The pre-mining but also

**FIGURE 6** Example of topography changes in the southern study area (compare overview map Figure 5). The overlay of the map of the Preußische Neuaufnahme on both maps shows in addition the good fitting of the historic DEM and the correlation of the old landscape structures to the new relief. Dashed red lines show the tectonic fault lines according to the geological overview map of North Rhine-Westphalia 1:100,000 [Color figure can be viewed at wileyonlinelibrary.com]

**FIGURE 7** Two examples of large-scale changes with (a) new positive landforms (Glessener Height) and (b) lowering the western edge of the Ville (previously open bit of Frechen) comparable to mountaintop mining. The overlay of the map to the Preußische Neuaufnahme on both maps shows in addition the good fitting of the historic DEM and the correlation of the old landscape structures to the new relief. Dashed red lines show the tectonic fault lines according to the geological overview map of North Rhine-Westphalia 1:100,000 [Color figure can be viewed at wileyonlinelibrary.com]
the post-mining topography relates to the location of the main tectonic fault lines. The natural relief shows the correlation of the elevated areas with the main fault lines. The actual extent of mining follows the fault lines, as they are accountable for the access to the lignite seams. The example for the refilling of the Frechen pit in the central part of the study area is an example of the tremendous change of the relief, but also of the hydrological situation. Here, some parts of the previously elevated part of the Ville horst are nowadays in use for flood protection, for example at the Boisdorfer lake, which is today at 74 m a.s.l. were the previous natural relief of the Ville was originally at 111.5 m a.s.l., which marks a significant lowering of the topography.

5.4 | The Ville as an Anthropocene landscape par excellence

The basic consideration of anthropogenic landforms as study objects in anthropogeomorphology is obvious, but can also be integrated into the Anthropocene idea and the ‘Critical Zone’ conceptual approach (Aguilar et al., 2020: 1). In this context, anthropogeomorphological studies are able to meet the need and challenge for broad interdisciplinary and transdisciplinary studies. The transformation of mining areas, although complex, can also be researched with this approach, in which the entirety from the vegetation cover to deep groundwater changes has to be regarded (Giardino & Houser, 2015). Studies with regard to post-mining landscapes and reclamation processes exist in various other disciplines (e.g., Krümmelbein et al., 2012; Larondelle & Haase, 2012; Menegaki & Kaliampakos, 2012; Hendrychova & Kabrna, 2016; Raab et al., 2016; Feng et al., 2019; Lowry et al., 2019; Wu et al., 2020). Mining induced relief changes incorporate also the socio-cultural fingerprint of humans to the landscape as part of the socio-cultural palimpsests (Tarolli et al., 2019). Therefore, consequences of mining, effects almost all spheres (atmosphere, biosphere, lithosphere, hydrosphere, and anthrosphere), so that mining landscapes constitute excellent examples for the Anthropocene.

In the study area, tremendous morphological changes occurred in less than 200 years. Although this alteration is only a snapshot in (geological) times, as the natural development of the Ville horst already started in Tertiary times, the anthropogenic changes, most probably, have a persistence for millennia. This constitutes for humans as main geomorphological agents (e.g., Price et al., 2011). In Central Europe, industrial surface mining impacts started in the late 18th and early 19th century. Crutzen and Stoermer (2000) proposed the Industrial Revolution as the onset of the Anthropocene. It is clear that the associated beginning of large relief changes cannot serve as stratigraphic Global Boundary Stratotype Section and Point (GSSP or ‘golden spike’) or Global Standard Stratigraphic Age (GSSA) (Zalasiewicz et al., 2015), as their development is highly diverse in the global context. However, the used historic maps from 1803 to 1820...
The natural topography of the oldest part of the current largest lignite district in middle Europe, the Ville horst in the southern Rhine Embayment. The focus of this contribution with a comparison of a computed historic DEM with the modern topography delimits our approach from other studies with their focus on the derivation of mining induced topographic signatures based on morphometric parameters of the nowadays relief (e.g., Chen et al., 2015; Tarolli et al., 2019; Cao et al., 2020).

The Ville area represents one of the oldest and largest anthropogenic mining landscapes worldwide. As reclamation is still a nascent discipline (Mossa & James, 2013), the region provides an excellent example to gain a better general understanding of long-term anthropogenic processes and their environmental impacts. The created historic DEM set the baseline for the mining induced morphological changes and can further be extended to the ongoing mining regions, but also to minimize ongoing disadvantageous earth surface processes, which is an ongoing challenge in geomorphology, respectively anthropogeomorphology (Tarolli & Sofia, 2016).

Given the size of the study area and the scale of interest, the produced DEM (30 m spatial resolution) is sufficient enough to represent the natural topography of the Ville before the mining and the associated relief differences in comparison to the relief after reclamation. Hence, the approximation for a suitable pixel resolution based on the contour spacing depending on their cumulative length over the study area and their maximal density as indicator for the complexity of terrain under investigation is a valuable approach. The results show that the vertical dimension in which the relief has transformed is at the scale of several decametres, both in positive and negative direction. New created landforms range from small-scaled heterogeneous and unplanned landforms in the southern part of the Ville, whereas large positive dumpsites with steep slopes characterize the northern part of the study area. The differences between the regions originated in the natural geological setting of the lignite strata but also in the technological development in mining and reclamation through time.

The regional scale of this study can be used for subsequent research questions at the local scale, for example for morphotectonic or hydrological changes of single catchments. It could be possible to investigate the natural topography at a higher spatial resolution in selected areas, as the initial point density varies over the study area and subsections could be expanded. Most scientific studies within post-mining landscapes focus on consideration of landscape functionality, ecology (including artificial soils) and subsequent land use, rather than the relief itself. However, primary geomorphological considerations should serve as a foundation, as many of the subsequent topics are significantly influenced by the relief. Thereby, anthropogenic geomorphology is of particular importance to clarify the human impact on landscapes, also for non-experts. Formerly mined and today recultivated or reforested areas do not always establish a direct connection for an indication of their enormous historic anthropogenic transformation. However, such changes will undoubtedly persist for a very long time and will therefore last as a human legacy far into the future, so that anthropogeomorphology can significantly support future Critical Zone research in the Anthropocene. In addition, a recommended extension of the results with regard to socio-cultural purposes can substantially contribute to the discussion about the Anthropocene in social sciences. Finally, an integration of questions about the perception of landscapes can significantly enhance a geographically human-environment perspective.

6 | CONCLUSION

In order to facilitate a detailed reconstruction of the pre-mining relief, historic maps (if available) are one of the most valuable sources, especially for comparisons with actual satellite or geodetic data. Here, the historic map of the Preußische Neufahndung from 1893 represents the natural topography of the oldest part of the current largest lignite district.
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DATA AVAILABILITY STATEMENT

The data of the final historic DEM that support the findings of this study are openly available at the Open Research Data from Heidelberg University (HeiDATA) via https://doi.org/10.11588/data/LSG8TN

DECLARATION OF INTERESTS

The authors declare that they do not have any conflicts of interest.

ORCID

Felix Henselowsky https://orcid.org/0000-0003-4145-7958
Daniel Kelterbaums https://orcid.org/0000-0003-1487-2304
Olfububenzer https://orcid.org/0000-0002-3199-1156

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