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Landform modifications in a glaciotectonic landscape as the result of complex mining activity: Case of the Muskau Arch Geopark, Poland

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Abstract

Mining activities lead to significant transformations of the original terrain, resulting in development of new post-mining landscape. The objective of this study was to assess the land transformations in the result of prolonged, underground and open-pit mining of shallow brown coal deposits in glaciotectonic structure of Muskau-Arch on the Polish-German border in the context of the geoheritage of this area. With this purpose, a geodatabase of thematic datasets representing progress of mining was developed in a geographic information system (GIS) based on topographical maps, mining plans, photographs, and digital elevation models (DEMs). The following timescales: 1903, 1911, 1937, 1955, 1972 and present-day were digitally reconstructed and quantitatively analysed using spatial processing functions including feature layer overlay and DEM differencing. The original, transitional and present-day landscapes were compared and visualised on five thematic maps and tables describing the spatio-temporal transformation of the natural landscape caused by underground and open-pit mining. Approximately 36.85% of the study area has been transformed, giving rise to the landscape of the present-day Geopark. The results provide insight into the genesis of its geoheritage. The adopted methodology, based on the historical GIS (HGIS) approach, can be applied to other post-mining sites, providing relevant documentation is available.

Keywords: Brown coal, post-mining, anthropogenic transformation, thematic mapping, spatio-temporal analysis, HGIS

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1. Introduction

Mining for mineral resources has been indicated as one of the key drivers of geomorphological change in the Anthropocene – epoch of significant human impact on Earth's systems – having a profound impact on landscape transformations (Goudie & Viles, 2016). Because of mining implications for geomorphic hazards (Zalasiewicz et al., 2011; Tarolli & Sofia, 2016) and impact on fluvial, as well as coastal processes (Brown et al., 2016) mining has become a focus of research. Mineral extraction and the associated industrial and construction activities have significantly altered landscapes worldwide, leaving behind transformations in landforms that persist long after these operations have ceased. Such changes include new features, often of considerable size, such as waste heaps, tailings ponds, open pits, subsidence basins, and embankments, which reshape the physical environment and impact ecological conditions, for example by causing deforestation (Białecka & Biały, 2014).

The character, size and extent of these anthropogenic transformations depend on the type of mining activity, as well as, to some extent, on the duration of mineral extraction. The new landforms usually remain visible in the landscape decades after the end of mineral extraction (Wójcik, 2008; Biały et al., 2020)

and present continuing challenges for land management and environmental restoration. Mining activities often lead to the creation of new characteristic landscapes with one of the most notable being lake lands (Blanchette & Lund, 2016; Koźma & Migoń, 2024). Additionally, adverse effects of mining can manifest itself, persist or intensify many years after the end of mineral extraction and successful reclamation processes. Examples of these processes include: flooding due to groundwater table restoration after end of mining drainage (Ignacy, 2021), sudden occurrence of sinkholes due to destruction of underground workings (Sahu & Lokhande, 2015), soil erosion (Sinha et al., 2017), acid mine drainage (Hancock et al., 2017), spontaneous combustion in mine spoil heaps (Abramowicz et al., 2020) and other ones. Therefore, post-mining areas, even after reclamation, require constant monitoring to analyse environmental conditions and support risk management activities that should be considered perpetual tasks (Kretschmann & Nguyen, 2020). In this regard, gaining precise knowledge about the extent of mining influence over time is valuable.

In studies of transforming landscapes, remotely sensed data such as aerial and satellite images and point clouds are especially useful and provide a source of information on the

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state of the Earth's surface at the moment of registration (Mulková & Popelková, 2024). These data sources have been applied to the study of mining activity and mining landscapes (Santo & Sánchez, 2002; Sklenička & Lhota, 2002; Carabassa et al., 2020). However, availability and applicability of these data can be limited especially when longer-time spans need to be analysed. Consequently, a hybrid approach integrating additional sources such as historical topographical maps, cadastral data, mining plans is necessary.

Given the characteristics of archival source data and their role in analysing mining related landscape changes, geographical information systems (GIS) with their data integration and analytical functions provide an indispensable environment (Knowles, 2013; Affek, 2013). In this paper we present a historical geographical information system (HGIS) approach coupled with descriptive statistics to analyse and assess the complexity of anthropogenic transformations of the landscape in an area of combined underground and open-pit brown coal mining in part of the Muskau Arch structure situated across the borders of Poland and Germany. The region, transformed by glacier ice (glaciotectonic) (Aber & Ber, 2007), was an important area of brown coal and clay industry, and owing to its rich mining and geological heritage (Świerkosz et al., 2016), presently constitutes part of the trans-border Muskau Arch UNESCO Global Geopark (Kožma & Kupetz, 2008; Koźma, 2011).

For the purpose of our study, we have enhanced the methodology applied previously in other studies of post-mining landscapes related to underground mining of hard coal and presented in (Wójcik, 2008; Jancewicz et al., 2020; Mulková & Popelková, 2024). The proposed approach based on a combination of geospatial data processing functions can be applied not only to mapping of anthropogenic landforms in the studied mining landscape but to other sites experiencing changes in the landscape in the world. The following study goals were established: (1) developing geodatabase documenting mining related changes in the landscape, (2) mapping the changing extent of anthropogenic landforms in the period of 1903–2021 to provide historical context for landscape evolution, (3) analysing mining-related landforms quantitatively, with a focus on their scale and spatial patterns, (4) assessing dynamics of spatio-temporal changes of anthropogenic landforms. These goals provide a reference framework for geomorphological and environmental analyses.

2. Theoretical Background

2.1 GIS for historical research

Published studies of landscape transformations caused by mining utilise approaches from the historical geographic information system (HGIS) domain, even when they do not explicitly use this term. HGIS can be defined as a set of tools, data, and methods aimed at collecting, processing, analysing, and sharing information about geographic space in the past. The primary research issues in this field include changes in land use and spatial planning, understanding historical settlement patterns, tracking environmental transformation, heritage studies and reconstructing historical landscapes and administrative boundaries (Affek, 2012). However, Knowles (2013) points to the extreme diversity of HGIS, with heterodox subjects and diverse range of sources.

Despite its ability to facilitate the analysis of different and varied sources of data in the spatial context, the HGIS based studies compel authors to assume a certain level of error. This is because obtaining historical data does not allow the use of precise measurement equipment as is possible for analyses concerning the present. When representing geographic space from the past, one

must rely on the accuracy of data from the studied period, and the further back in time we go, the lower the precision becomes (Szady, 2008). This aspect has been reviewed by Hvizdák et al. (2023) who presented a methodology for processing historical mine maps with the possibility of their further use for the purposes of mining tourism.

2.2 HGIS approaches in analysis of post-mining landscapes

Published research utilising the HGIS approach for landscape analysis in post-mining sites include the work of Fonte et al. (2021), who mapped ancient tin mining remains in a valley in northern Portugal by integrating airborne LiDAR and historical aerial imagery. Their study analysed the impact of modern mining and identified the best-preserved historical mining areas for further archaeological research. Wójcik (2013) based on a study of historic maps and documents identified anthropogenic inversion of relief in the Walbrzych Hard Coal Basin (Poland) and assessed that 63% of the study area was affected by mining related transformation of landscape. In comparison, Dulias (2016) based on the results of two different methods based on raw-material output and morphometric analysis estimated the extent of anthropogenic denudation in Upper Silesia Coal Basin (Poland) between the mid-18th century until 2009.

Recently, Romańczukiewicz and Górnjak-Zimroz (2025) investigated long-term (1884–2023) landscape changes caused by mining of granite in the Strzelin region of Poland utilising a methodology of integrating historical cartographic materials with present-day geospatial data such as orthophotomosaic in GIS. They have reported problems with correct identification of land cover classes due to various scales, symbols and accuracy of historical data. An even longer period (1845–2050) was analysed by Hendrychová and Kabrna (2016). They have focused on the cumulative effect of the mining industry on the landscape and changes in landscape diversity in an area subjected to both underground and surface mining while also evaluating the planned outcome of revitalisation of the landscape currently used for mining. They studied the Most region in the Czech Republic using historical cadastral and military maps. The reported factors that influenced the accuracy of this analysis included data quality, method of processing and precision in digitising individual landscape features. A different approach was presented in Ang et al. (2021) who utilised Landsat satellite imagery to calculate spectral indices and applied machine learning classification technique to analyse land cover change caused by mining in a study area located in the Philippines. However, they analysed a much shorter period (1994–2018). Elsewhere, Mulková and Popelková (2024) conducted temporal and spatial analyses using vector data derived from a series of aerial photographs in part of the Ostrava-Karviná coal mining area in the Czech Republic. Their study presented that photogrammetric data can effectively be applied to monitor spatio-temporal changes in land cover. In a study by Schuchová et al. (2023) complex geomorphological investigations of underground abandoned slate mines in the Czech Republic were conducted, which have been found crucial for evaluation of nature, risk assessment, remediation and tourist management of such abandoned mining sites. Kupka and Stalmachová (2023) evaluated the natural and ecological parameters for the possibility of declaring the aquiferous subsidence basins in the same Karviná region in the category of a small-scale special protection area. Kubalíková and Balková (2023) investigated threats to geodiversity and geoheritage in the Hády Hill area of Brno, Czech Republic.

Despite the growing number of research applying historical GIS to the analysis of post-mining landscapes, several limitations remain. Existing studies predominantly focus either on land cover change, relief transformation, or ecological assessment, often within isolated temporal frameworks. The integration of HGIS with

spatial modelling, 3D reconstruction, and multi-source data fusion remains underexplored, especially in the context of reconstructing pre-mining glaciotectionic landscapes and linking them to present-day geomorphological features. Moreover, relatively few studies combine long-term historical interpretation of mining-induced landforms in regions shaped by both underground and surface mining where overlapping landscape impacts demand a specific analytical approach, as undertaken in this paper.

3. Area under study

3.1 Geological context and history of mining

The study area, the ‘Pustkow’ mining field of the ‘Przyjaźń Narodów – Szyb Babina’ (‘Babina’) mine, is situated between the town of Łęknica on the Polish-German border and the villages of Nowe Czaple and Bronowice to the north-east (Fig. 1). In terms of the geomorphology, the area is located in the south-eastern part of the above-mentioned push moraine known as the Muskau Arch. It was originally formed during the Elsterian (MOIS 12) glaciation and was subsequently remodelled during successive glacial periods (Kupetz, 1997; Badura et. al, 2003). The solid basement rocks occur at depths of more than 220 m below the ground and have no direct influence on topography. The overlying Cenozoic formations were deposited between Late Oligocene and Pliocene and comprise several clastic formations, accumulated in alternating fluvial, lacustrine and coastal environments (Kožma & Migoń, 2024). The

stratigraphic profile of the study area includes, apart from 4 brown coal seams, sands, gravels, till and kaolin clays, silts, and loams (Dyjur, 1970; Oberc, 1972; Kasiński & Słodkowska, 2017).

The evolution of glacial landforms in the Muskau Arch area was multi-staged. Successive glacial processes led to folding, upthrust and subsequent erosion of initially lower lying and covered deposits that included brown coal seams (Urbański, 2007). The oldest ice-sheet advance in the Elsterian produced three main parallel arcs of push moraines. Next, the older Saalian ice sheet (MOIS 6) deeply eroded and truncated most of the elevated parts. Further denudation by non-glacial processes gave the area its complex appearance, including unblocking the flow of the Nysa Łużycka River to the north. Then it was then heavily modified by mining and related industrial activities (Dyjur & Chlebowski, 1973; Kupetz, 1997; Kupetz & Koźma, 2015; Koźma & Migoń, 2024).

Outcrops of heavily folded brown coal layers on the surface have been subjected to weathering, which led to reduction in volume due to oxidation resulting in terrain hollows, locally known as gisers (Kupetz, 1997; Koźma, 2017). Exposed and shallow brown coal deposits contributed to the beginning of coal mining in the western part of the Muskau Arch as early as 1843. In the Eastern part of the structure (contemporary Poland), coal extraction began a few years later, in 1854 (Kožma, 2016). The largest mine in this part of the Muskau Arch was the ‘Babina’, which is the subject of our study, established initially by the German company Braunkohlen- und Brikett-Industrie A.G. According to archival

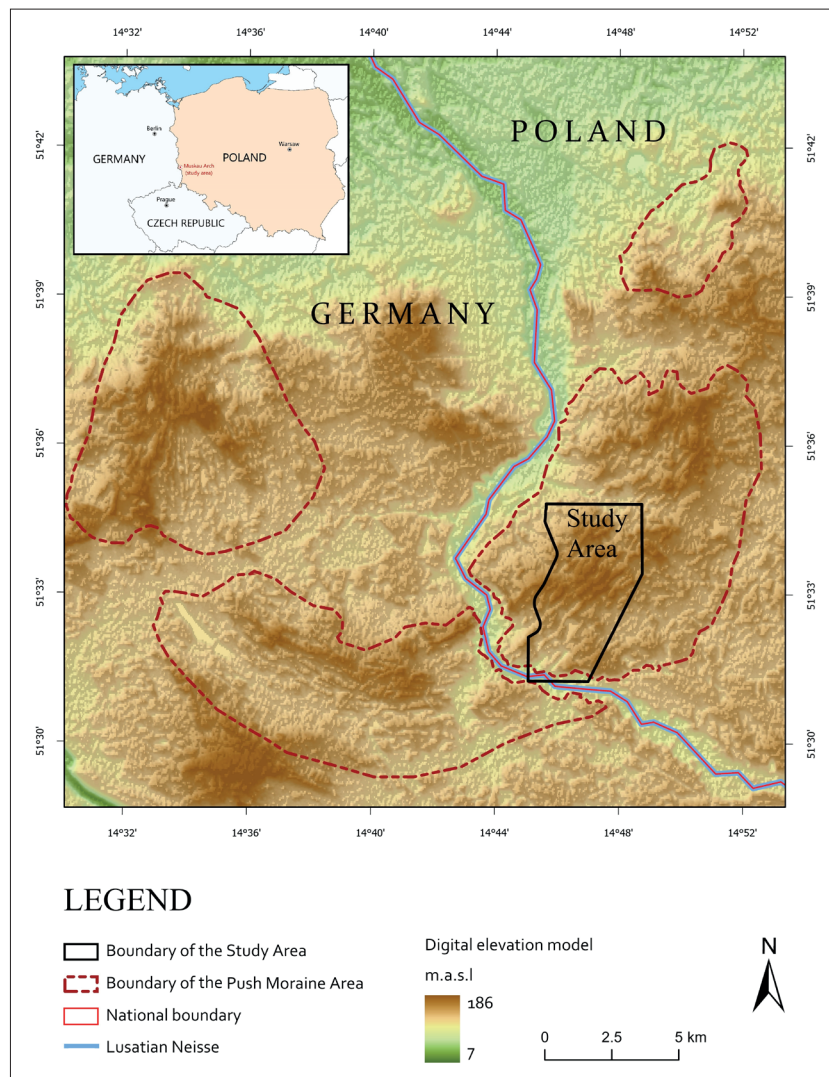


Fig. 1: Location of the study area

Source: Authors' elaboration based on background Copernicus DEM, the boundary of push moraine after Koźma & Kupetz (2008)

documents, mining operations started in 1903, but brown coal exploitation on an industrial scale began in 1921. Initially, the deposits were mined mainly with an underground method, and with time open-pit mining became predominant. After World War II the study area became part of Poland, and open-pit and to some extent underground mining continued until 1973 when the mines were closed due to unfavourable geological conditions and for economic reasons (Badura et al., 2003; Greinert et al., 2015). A photograph from the 1960s and depicting part of the largest open-pit is presented in Figure 2.

More than 50 years of mining operations resulted in substantial degradation of the area initially covered, mainly, by coniferous forests and remodelling of the terrain surface that included subsidence basins over underground mines, sinkholes from shallow mining, development of numerous open pits and waste heaps, as well as earth works associated with transport infrastructure and processing of brown coal, e.g. briquetting plants. Extensive reclamation works were undertaken in the 1970s with the aim to restore natural values of the land. These involved reforestation, technical preparation and formation of anthropogenic lakes in numerous open-pits. Field investigations showed that remediation works aimed at reforestation failed in many parts (Greinert et al., 1997; Greinert et al., 2015). These actions were repeated in 1986, but only in some parts of the degraded area. Later on, the area underwent natural reclamation processes that resulted in creation of a post-mining lake landscape.

3.2 State of knowledge on the post-mining conditions in the Muskau Arch area

The Muskau Arch, especially its geology, geomorphology, history of brown coal mining and subsequent rehabilitation already have been the subject of various studies. Some of these works

included geographic information system (GIS) based cartographic representations and quantitative spatial analyses but so far to a limited extent. Notably, Kupetz (1997) and later Urbański (2007) described the complex structure and glaciotectonic genesis of the Muskau Arch moraine focusing on the German and the Polish parts respectively. The sedimentation conditions and stratigraphy of brown coal deposits in this area have been presented by Kasiński and Słodkowska (2017). Koźma and Kupetz (2008) characterised the geology and typical landscape forms found in the Muskau Arch, as well as identified and classified the types of geotopes found in this area. Their work was followed by Koźma (2011) who described the transboundary Muskau Arch Geopark. Earlier, Greinert et al. (1997) described the development of an anthropogenic lake district, after the end of mining. Brown coal mining in the entire Lubuskie region (Western Poland), including the Muskau Arch area was the subject of the monograph edited by Greinert (2015). The legacy of mining activities in the region has been analysed by Gontaszewska (2015) who investigated the problem of secondary surface deformations, including the study area.

Published studies of post-mining lakes condition include research by Sienkiewicz and Gąsiorowski (2016, 2019) who analysed evolution of artificial lakes acidity formed in brown coal excavation sites based on diatom, geochemical and isotopic data. These authors also studied the influence of acid mine drainage on the phyto- and zooplankton communities in a clay pit lake (Sienkiewicz & Gąsiorowski 2018). Gąsiorowski et al. (2021) followed with a study of geochemical variability of sediments and their relation to water chemistry.

Furthermore, Oszkinis-Golon et al. (2021) studied thirty of post-mining lakes to identify the main factors influencing the diversity of macrophyte vegetation growing under very extreme and diversified habitat conditions. The values for geotourism of



Fig. 2: Archival photograph of the open-pit in the 'Przyjaźń Narodów – Szyb Babina' mine ca. 1964–1967
Source: National Archive in Zielona Gora, Photo by C. Luniewicz

the natural and transformed landscape have been discussed by Koźma (2017). In addition, Świerkosz et al. (2016) put forward the proposal of an integrated approach to protecting geo- and biodiversity in the area.

Recent research shows that numerous processes resulting from past mining activities continue there. These include sinkhole prone sites (Blachowski et al., 2022), gully erosion of exposed spoil heaps (Blachowski et al., 2023a), waterlogging of subsided zones and vegetation changes (Buczyńska et al., 2023). In the past few years, studies utilising satellite remote sensing data for assessment of vegetation condition have been conducted by Buczyńska et al. (2023), Blachowski et al. (2023b) and Buczyńska and Blachowski (2023). In the first two studies, the authors applied spatial statistics methods to analyse vegetation spectral indices used as proxies for land cover condition assessment based on 30 years of data from Landsat satellite and followed this with map algebra and spatial autocorrelation of Sentinel 2 derived spectral indices to investigate a vegetation condition for an 8-year period. Moreover, in the last publication a new mining and geology Impact Factor (MaGIF) index for assessment of the post-mining environment based on results of previous studies in the Babina mine area was proposed. In the latest study, evolution of surface water area was investigated (Smentek et al., 2025). Most recently, Koźma and Migoń (2024) have described glacial and post-glacial processes, as well as anthropogenic transformations caused by mining and provided several maps presenting locally geomorphological and post-mining landscapes, which aligns with the topic of our study.

4. Materials and methods

Our research utilised available archival topographic maps, mining maps, geological cross-sections, photographs, as well as present day national databases of topographical objects and digital elevation models (DEMs) derived from aerial laser scanning (ALS). These data are listed below together with their main specifications and application in our study for the benefit of replicability of our study:

- Mining maps: from the archive of the Higher Mining Authority drawn at a scale 1:1,000 representing location and extent of underground mining plans and open-pits. The preserved 67 map sections date back to the 1960s and do not cover the entire area of our study. These materials have been used to map the extent of underground and open-pit mining.
- Geological cross-sections: the available 92 documents prepared at a scale 1:500 in 1967 were used as supplementary material for mapping the location of underground and open-pit mining.
- Archival topographical maps (*Messtischblätter*): old German topographic maps drawn at a scale of 1:25,000. The available maps were produced in 1847 (Prussian *Urmesstischblatt*), 1903, 1911, 1928 and 1939/40, and were used to map anthropogenic landforms such as open-pits and waste tips, construct digital elevation model of the study area prior to significant mining activity, to analyse evolution of anthropogenic transformations.
- National database of topographical objects (BDOT10k): corresponds to the content of a traditional topographic map at a scale of 1:10,000. The GIS feature layers were used to map and analyse present-day land use and land cover of the post-mining study area, e.g. anthropogenic lakes.
- Digital elevation models (DEMs): based on the Aerial Laser Scanning (ALS) missions commissioned by the Polish National Centre of Geodetic and Cartographic Documentation in 2011 and 2021a. The horizontal spacing is 4 points per 1 m², whereas the vertical error does not exceed 0.05–0.15 m according to their metadata. The newest DEM was used as a basic source of information on the spatial extent of anthropogenic landforms, through manual digital coding of surface features, as well as deriving slope and hillshade (shaded relief) products in GIS.

- Archival photographs: depicting open-pit mining and associated industrial activities in the study area dating back to the mid-20th century were obtained from Internet databases such as www.fotopolska.eu, National Archive in Zielona Gora, as well as the non-profit Muskau Arch Geopark Association. A photograph representing a large open-pit operation in the study area is shown in Figure 2.
- Present-day photographs depicting contemporary topography of the study area were acquired during field visits using an unmanned aerial vehicle and hand-held cameras.

Our approach to the analysis of landform transformations is based on the set of thematic maps presenting spatial evolution of the landscape and a general map presenting spatial distribution and variety of present-day anthropogenic landforms in the studied part of the Muskau Arch glaciotectonic post-mining area. The maps are accompanied by descriptive statistics providing quantitative information on the changes. For these purposes a GIS geodatabase was developed. It contains: raster datasets representing scanned cartographic documents, digital elevation models and their derivatives, point, line and polygon vector feature classes representing identified landforms and their evolution in time, as well as land cover and land use objects. In the study we used free and open source GIS software QGIS, and ESRI ArcGIS Pro software licensed to Wrocław University of Science and Technology. The general workflow of the study is presented in Figure 3.

The thematic maps are presented in the results section and comprise of:

- Map (Fig. 4) of the lithological and morphological image of the original pre-mining landscape;
- Maps representing evolution in time of the main anthropogenic landforms associated with mining, separately for open-pit (Fig. 5) and underground mining (Fig. 6);
- Map (Fig. 7) representing extent of the landscape transformed by mining;
- Perspective view (Fig. 8) of anthropogenic landforms in the study area;
- General map (Fig. 9) representing the spatial distribution of anthropogenic landforms that resulted from both underground and open-pit mining.

The map presented in Figure 4 was constructed through manual digitisation of features depicted in the 1847 and subsequent topographical maps drawn prior to the start of brown coal mining. It presents qualitative information based on the interpretation of these sources. The thematic layers that represent lithological and morphological images are semi-transparent to highlight the

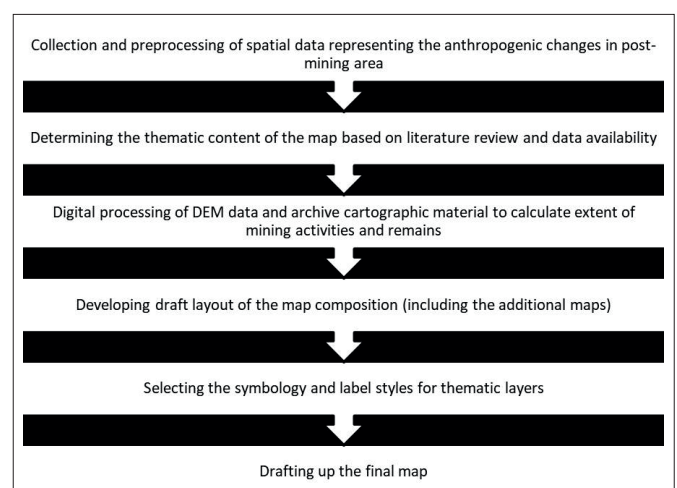


Fig. 3: The general workflow of the study
Source: Authors' conceptualisation

shaded relief background. The latter was prepared through manual digitisation of isolines and spot elevations in the Messtischblatt to develop a digital elevation model using spatial interpolation technique and GIS hillshade function.

To construct maps presented in Figures 5 and 6, the main anthropogenic landforms, such as open-pits, and subsidence basins were identified from interpretation of available topographical maps and digital elevation models. These were coded as vector features with a time attribute representing the date of document these landforms are presented on (1903 to 1972). The graduated colour palette was used to distinguish the temporal evolution of anthropogenic landforms associated with mining.

The map (Fig. 7) was constructed based on the result of DEM differencing where the elevations of the older 1911 DEM were subtracted from the elevations of the newer 2021 DEM on a cell by cell basis. Prior to differencing both DEMs were resampled to 5 m spatial resolution. Due to the lower accuracy of the 1911 DEM constructed through digitisation of the topographical map drawn at the scale of 1:25,000 and spacing of isolines between 1.25 m and 5.0 m we made an assumption that elevation difference between -1.0 and $+1.0$ is represented as no change. Visualisations of the present-day morphology (Fig. 8) was constructed as a gradient shaded digital elevation model with superimposed anthropogenic lakes in place of old open-pits and flooded subsidence basins. We used the DEM dataset from 2021. The morphology is presented in a perspective view. The GIS geodatabase was subsequently used to calculate the basic spatial descriptive statistics such as minimum, maximum, total and share of total area. In case of raster data zonal statistic functions were used. The results are presented as tables and graphs.

5. Results

5.1 Natural landforms

The original landforms in the study area are presented in Figure 4. This lithological and morphological image of the original pre-mining landscape resulted from successive glacial and erosional processes. The landscape consisted of alternating hills and depressions running approx. from the NNE to SSW direction towards the Nysa Łużycka River Valley that cuts across the moraine in the southernmost part of the analysed site. The original terrain elevations ranged from approx. 186 m a.s.l. to approx. 100 m a.s.l. in the river valley with the elevation differences between the elongated hills and depression between them ranging from 10 to 30 m. Characteristic features of the undisturbed landscape included moraine hills made of sands, gravels, boulders, separated by terrain depressions with peats, silts and fine sands, as well as weathered of brown coal outcrops (gisers), and sometimes localised wetlands. The spacing between crests of adjacent ridges separated by depressions ranged from approx. 200 m to 500 m. The area was naturally drained towards the Nysa Łużycka River in the south. There were just a few small natural surface water bodies. It should be noted that the giser features have not been reported from anywhere else except the Muskau Arch.

5.2 Spatio-temporal evolution of open-pit mining

The present-day morphological image of the study area differs substantially from its pre-mining state. It has been presented from different perspectives in Figures 5 and 6. Figure 5 presents the spatial and temporal evolution of open-pit mining. The darker shades of brown represent the older pits, with lighter browns

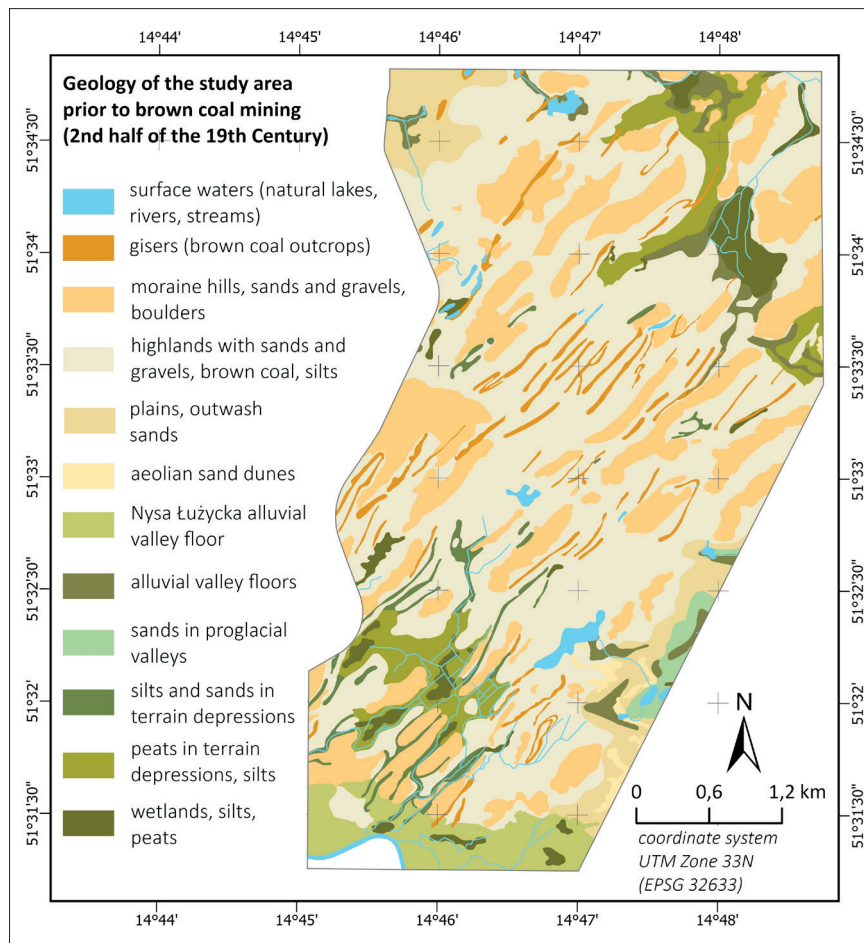


Fig. 4: Lithological and morphological image of the original pre-mining landscape in the study area superimposed on DEM prior to brown coal mining (2nd half of the 19th century)

Source: Authors' elaboration

showing the younger ones. The open-pit mining in the analysed part of the Muskau Arch started in the north-east part with small scale operations (darkest brown areas) and gradually progressed towards south-west. The excavations followed the extent of the brown coal deposits that were transformed by the glacier to form scale-like shapes. Some of the small pits were associated with clay mining. The first larger open-pits, visible in the middle part of the study area, date back to the 1930s. The most numerous and largest open-pits date back to the 1950s until late 1960s and termination of mining in the area.

5.3 Spatio-temporal evolution of underground mining

Figure 6 represents the spatial and temporal evolution of underground mining. The darker shades show areas of the oldest shallow underground activity, the lighter subsequent younger underground mining. In the analysed part of Muskau Arch the oldest underground mines, dating back to pre-World War II, were located in the central and eastern parts of the Pustków field. The mining continued towards the Nysa Łużycka Valley. The youngest underground mines, which are located in the western and north-western parts, have characteristic elongated shapes that follow the folded brown coal deposits. In the western part both wings of the deposit were mined, whereas in the north-western one just the eastern wing of the scale-like deposit was mined.

5.4 Elevation change due to mining activities

The map shown in Figure 7 presents the results of DEM differencing that indicates zones of modification of original landform due to prolonged open-pit and underground mining or

the associated industrial activity. The areas of elevation increase are marked with warm (red) colour, the areas of terrain lowering with cold (blue) colour, whereas the parts that did not change by more than ± 1.1 m are represented as gray. This threshold value was set based on the accuracy of historical materials. The descriptive statistics calculated with the zonal statistic function in GIS are given in Table 1. We estimated that approx. 19% (4.17 km²) of the total study area (21.02 km²) was elevated between 1911 and 2021, 33% (7.28 km²) underwent excavation or subsidence. Approx. half of the analysed area (48%) was not directly affected or the change was compensated by operations such as filling in an old open-pit. The greatest elevation change calculated from the DEM differencing amounts to 48 m. Due to the applied necessary generalisation related to the lower accuracy of the DEM constructed from the digitised topographical map drawn in 1911 these results should be considered as indicative.

Nevertheless, they provide the best available approximation. It should be noted that the main zones of landform elevation change are spatially congruent with the limits of mining activity (black outline in Figure 3 determined from interpretation of available mining documentations. The main subsidence sites are associated with locations of open-pits (presented in Fig. 5) and underground mining fields (presented in Fig. 6). The elevated sites are predominantly located within boundaries of old waste heaps. Additionally, some of the registered changes can be associated with contemporary construction works such as the development of a road bypass.

The perspective view shown in Figure 8 represents the study area looking from south-west towards north-east and provides a wider spatial context of the analysed post-mining area located

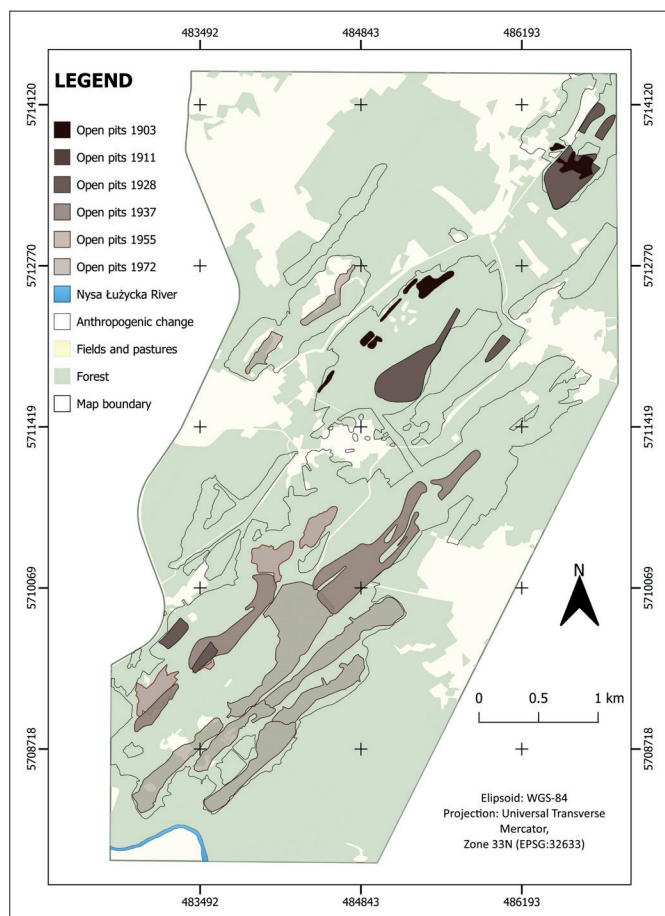


Fig. 5: Evolution of open-pit mining determined from interpretation of historical topographical maps and digital elevation models (the dates in the legend indicate the year when the features first appeared in source materials)

Source: Authors' elaboration

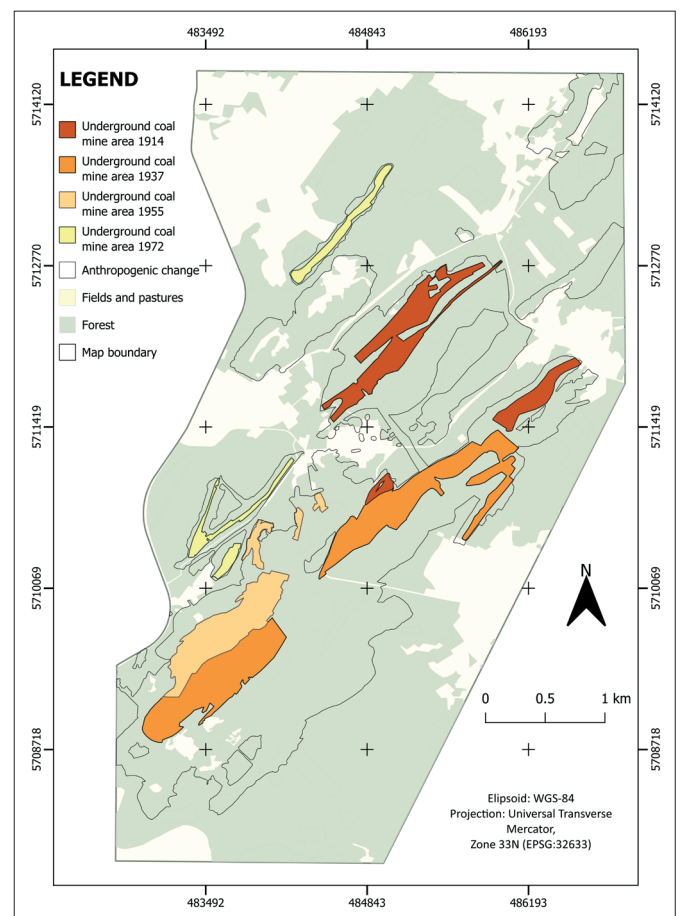


Fig. 6: Evolution of underground mining determined from interpretation of historical topographical maps and digital elevation models (the dates in the legend indicate the year when the features first appeared in source materials)

Source: Authors' elaboration

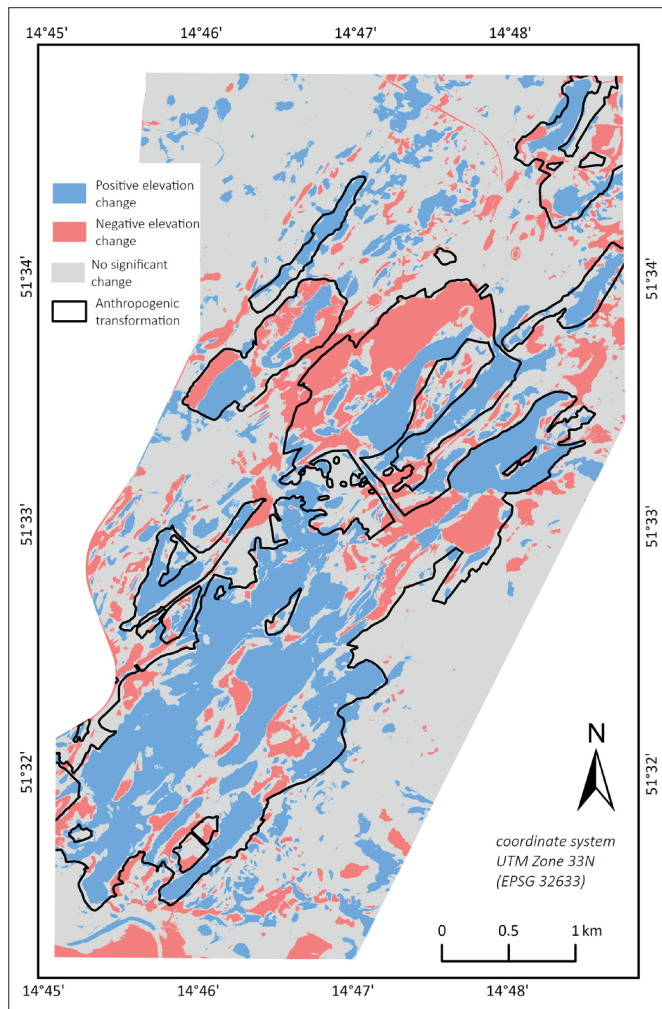


Fig. 7: Relative elevation change map of the analysed part of the Muskau Arch area obtained from differencing digital elevation models (1911, 2021)
Source: Authors' elaboration

in the Muskau Arch eastern arm with the Nysa Łużycka river dissecting the terminal moraine into two distinct parts. The original landscape (Fig. 4) characterised with gentle parallel hills separated by shallow valleys was remodelled. Presently the characteristic feature of the area includes numerous anthropogenic lakes (blue areas) that formed in abandoned open-pits. The more circular or arrow-shaped lakes are the result of land subsidence over former shallow underground mining and subsequent rise of groundwater level after the end of mining drainage. There are also man-made waste heaps next to old open-pits. These features often replaced the older natural depressions (*gisers*). Thus, these artificial landforms contributed greatly to present-day landscape diversity. The linear features cutting across the area are the remains of old transport roads and railways with many reused as tourist trails.

The locations of the preserved brown coal outcrops, subjected to more intense weathering, which leads to reduction in volume due to oxidation, form shallow terrain depressions that can be traced over several kilometres. Their typical depth is 3 to 5 m with some of them deeper. The shapes and spatial patterns of *giser* approximate the geometry of deposits reshaped by the glacier movement and ice sheet loading. Within the thrust sheets the terrain depressions (*gisers*) are 1–2 km long and keep constant width and strike, whereas those associated with structures formed by upward movement of lower lying deposits have irregular courses and variable width. The least altered and best-preserved features of the natural landscape structure include the wide river valley of the Nysa Łużycka River cutting through the moraine

Type of change	Area (m ²)	Share of total area (%)
Positive elevation change	4,193,100	19
Negative elevation change	7,276,959	33
No significant change	9,559,813	48
Total area	21,030,966	100

Tab. 1: Descriptive statistics of elevation changes in the study area derived from differencing digital elevation models from 1911 and 2021
Source: Authors' calculations

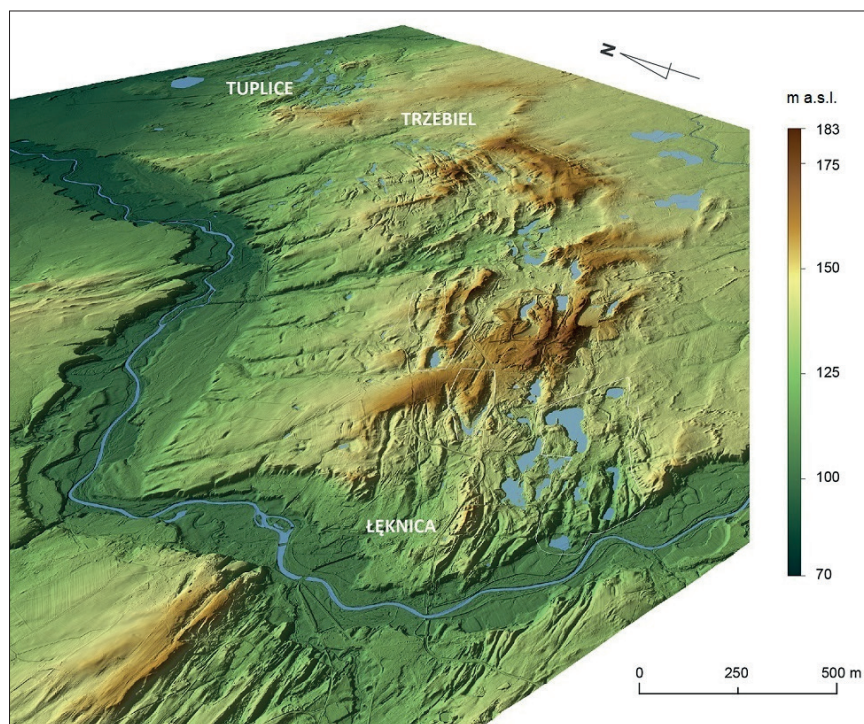


Fig. 8: Perspective view of the post-mining study area in the spatial context of the eastern arm of the Muskau Arch structure
Source: Authors' elaboration

ridge and other smaller lower-order alluvial accumulation forms, as well as the proglacial plains surrounding the Muskau Arch, along with the associated dune forms.

5.5 Spatial representation of post-mining features

The spatial distribution of the identified natural and anthropogenic landform features are shown in Figure 9. The choice of symbols and fill colours reflect the morphological properties of landforms, with cold tones assigned to concave forms and warm tones to convex ones. Cartographic symbols were carefully designed in accordance with the principles of graphic design to ensure legibility, visual contrast, figure-ground organisation and hierarchical composition.

Altogether 20 different feature categories can be distinguished. These include areal features related to underground and open-pit mining such as: underground mining fields, subsidence basins from underground mining, anthropogenic water bodies, former brown coal and clay open pits, waste material heaps, open pits filled with waste material. The map also depicts brown coal outcrops (*gisers*), which are unique for this area.

Linear and point features associated with mining activity consist of tourist trails following former transport tracks and dismantled railway lines, location of underground mine entrances

and industrial ruins. To complete the picture present-day main land use types comprising forests, fields and pastures, built-up areas, main and secondary roads, rivers along with contour lines representing the relief are presented.

It is worth expressing that the landforms associated with underground and open-pit mining are adjacent to each other or in many cases are spatially congruent (overlapping). These superpositions of mining features include open-pits were developed in areas previously mined from underground, waste heaps were established over underground mines or new lakes formed in former open-pits.

5.6 Statistical analysis of landform change

The descriptive statistics detailing the number and sizes of post-mining features depicted in Figure 9 are given in Tables 2 to 5. Table 2 presents the descriptive statistics of the main landforms that result from mining operations in the study area.

According to our interpretation of available historical records the area transformed due to prolonged industrial activity in the studied part of the Muskau Arch structure covers approx. 7.75 km² (7,750,106 m²), which constitutes 36.85% of the total study area (21,030,966 m²). The area under direct or indirect influence of shallow underground mining, e.g. with identified subsidence basins,

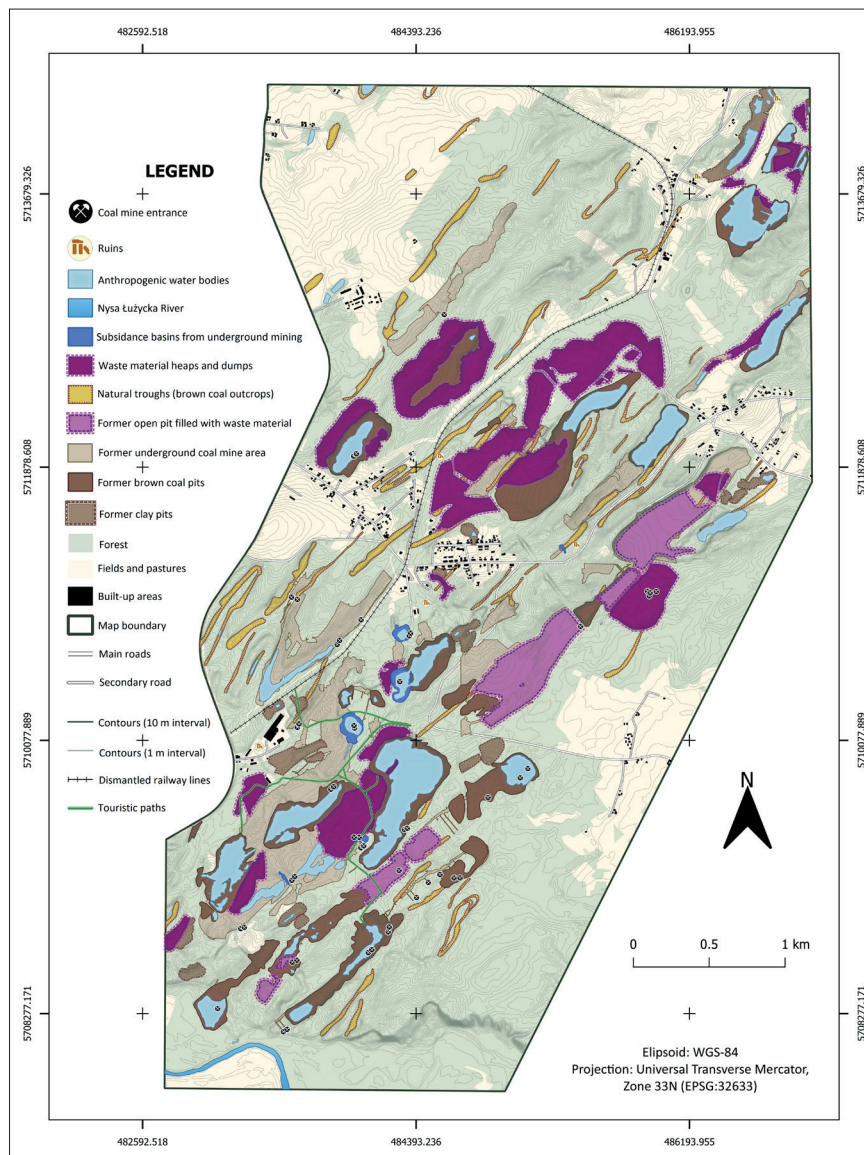


Fig. 9: The imprint of historical mining on the contemporary landscape
Source: Authors' elaboration

Feature type	Statistic	Area (m ²)	Share of the study area (%)	Number of features
Underground coal mine areas	Min	34	6.4	28
	Max	789,214		
	Mean	48,177		
	Total area	1,348,959		
Brown coal pits	Min	2,115	3.4	22
	Max	69,675		
	Mean	31,063		
	Total area	714,447		
Clay pits	Min	1,557	0.8	19
	Max	47,336		
	Mean	9,448		
	Total area	179,510		
Open pits filled with waste material	Min	5,878	2.3	7
	Max	211,341		
	Mean	70,133		
	Total area	490,932		
Waste heaps and dumps	Min	370	5.9	33
	Max	197,749		
	Mean	37,764		
	Total area	1,246,204		
Water bodies	Min	106	4.2	57
	Max	181,653		
	Mean	15,668		
	Total area	893,058		

Tab. 2: Descriptive statistics for selected landforms shown in map on Figure 9
Source: Authors' calculations

sinkholes, as well as access works covers approx. 6.4% of the total study site. The area of positive (elevated) forms in the contemporary landscape such as waste heaps amounts to about 5.9%. The lakes that formed in abandoned open-pits cover approx. 4.2%, whereas the open-pits that were filled with waste material, e.g. overburden from newer excavations amount to 2.3% of the area. As can be seen in Table 2, the sizes of the particular landforms differ greatly between features in each group type. This can be partly attributed to the complex geology and natural landscape of the area prior to mineral extraction, which to some extent dictated the mining system and the configuration of excavation works. As a result, these conditions influenced the morphology of post-mining features, such as subsidence basins, open pits, and lakes formed in sinkholes above shafts or excavations, which often reflect the shapes of the original mining structures.

In total, 57 surface water bodies have been identified. The smallest of these is approximately 106 m² and the largest one 181,653 m². Also, the sizes of the 33 identified waste heaps vary between 370 and 37,764 m². In comparison, the sizes of open pits range from 1,557 to 70,133 m², with the smallest ones resulting from clay mining. It should be noted that the relative elevation differences of the largest waste heaps remaining in the study area measuring from the foot to the top reach 17–18 m. In case of the remains of open-pit the elevation differences reach 8–9 m.

Year	1903	1911	1928	1937	1955	1972
Min	4,779	4,779	15,394	41,932	5,779	85,945
Max	36,656	36,656	160,085	283,130	74,886	313,353
Mean	13,703	12,737	63,028	102,656	40,669	158,772
Total area	95,919	101,898	378,170	513,278	203,346	952,632

Tab. 3: The evolution of the area of open-pit mining in 1903–1972 period (in m²). Source: Authors' calculations

Tables 3 and 4 contain the statistics for the underground and open-pit mining between 1903 and 1972. The graphs presented in Figures 10 and 11 indicate the share of open-pit mining and underground mining in the analysed period respectively. Analysis of open-pit mining shows gradual increase until the World War II (last available cartographic material dates back to 1937), temporary decline in the first years after WWII, and subsequent growth until the decision to end mining at the end of the 1960s (the most recent cartographic material comes from 1972). Overall, approx. 4.5% of the study area was taken by open-pits, not including the associated landforms such as heaps and transport infrastructure. Analysis of underground mining indicates gradual growth until World War II and steady decrease thereafter. This is connected with the gradual shift to open-pit mining. At the peak, approx. 5.6% of the study area was used for excavation of brown coal through underground mining.

Finally, the statistics on the anthropogenic lakes that formed after the end of open-pit operations (Tab. 5) highlight the varying contributions of different types of anthropogenic lakes to the overall landscape. In the studied part, the lakes in open-pits (660,587 m²) cover approx. 3.1% of total area, and approx. 8.5% of the land transformed by mining. The area covered by water bodies that formed above underground mines is smaller (72,708 m²) and takes 0.3% and 0.9% of the total study area

Year	1911	1937	1955	1972
Min	–	441,485	11,047	25,515
Max	–	747,340	344,425	79,490
Mean	–	594,413	101,366	56,239
Total area	329,253	1,188,825	405,463	168,716

Tab. 4: The evolution of the area of underground mining in 1911–1972 period (in m²). Source: Authors' calculations

Statistic	Anthropogenic lakes in old open pit	Anthropogenic lakes in subsided areas	Other lakes
Total area (m ²)	660,587	72,708	143,222
Area/Total study area (%)	3.1	0.4	0.7
Area/Anthropogenic change (%)	8.5	0.9	1.8

Tab. 5: Descriptive statistics for the surface water bodies in the study area. Source: Authors' calculations

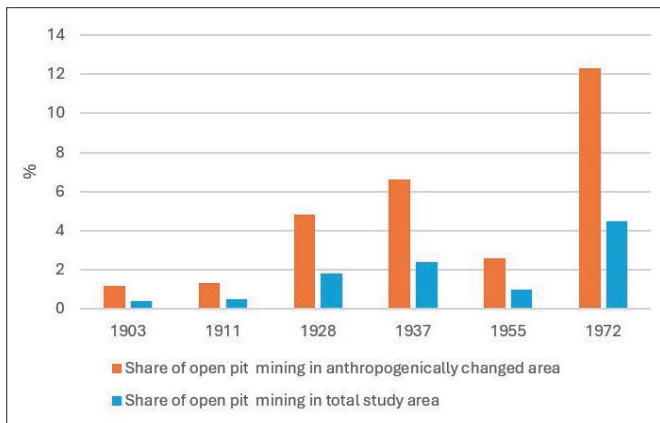


Fig. 10: Share of open-pit mining area in the study area in the 1903–1972 period. Source: Authors' elaboration

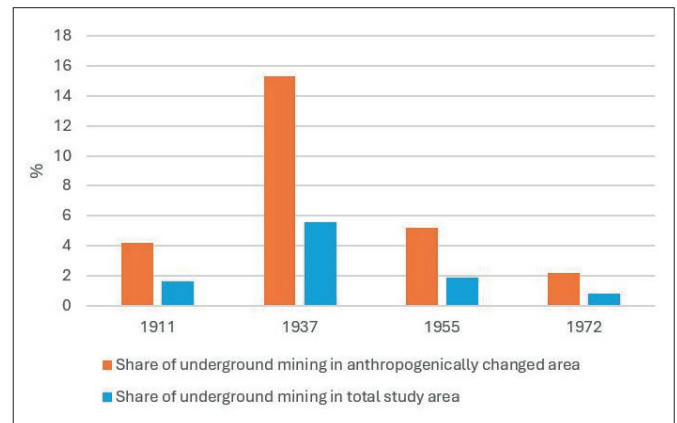


Fig. 11: Share of underground mining area in the study area in the 1911–1972 period. Source: Authors' elaboration

and area impacted by mining respectively. Together with the other lakes located outside the determined extent of mining and probably of natural origin (143,222 m²) these water features account for the characteristic present-day landscape of this part of the Muskau Arch structure.

5.7 Field investigations

Our study was accompanied by field investigations, the most carried out between 2023 and 2024. Two selected photographs from site investigations present a contemporary view of the post-mining landscape. These are distinct examples of the representative features that are characteristic for the study site that now constitutes a fragment of the transborder UNESCO Global Geopark.

The first one (Fig. 12) is an aerial image taken in March 2024, and shows present-day landforms and land cover in the southern part of the post-mining area, which is representative for the entire study site. In the foreground, small lakes of anthropogenic origin that developed in former brown coal open-pits are visible

(A). Some of the open-pits have been filled (B) or partially filled with waste material from other excavations (C). In the other parts external waste heaps have been developed (D, E). These anthropogenic landforms, due to unsuccessful reclamation in the 1970s and 1980s, are mostly devoid of vegetation and undergo erosion processes that produce large gullies. The same processes occur on slopes of old open-pits filled with waste. These features are situated in close proximity to a zone affected by underground mining activity (F). The forest road (G) constructed in the place of the old transport road is a sign of new tourist development connected with the establishment of the Geopark in the region. The new visitor infrastructure includes: numerous viewing points, exposed remains of mining works, educational trails, picnic sites, information boards, and a large viewing tower. These features have been set-up to present the rich geological and mining heritage of the area.

The second view (Fig. 13) represents the contemporary anthropogenic lake 'Afryka' that was formed in place of the largest open pit that was operational in the 1960s (in contrast to



Fig. 12: Contemporary view of the southern part of the study area taken with drone photography. The letters indicate: A. flooded former brown coal open-pit, B. part of the former brown coal open pit filled with waste material from another excavation, C. former brown coal open-pit, partially filled with water, D. external, exposed, waste heap, E. external, exposed, waste heap, F. zone of former underground mining, G. present-day road (tourist educational trail). Photo: M. Becker (2024)



Fig. 13: View from the east bank of the largest anthropogenic lake, in the front view eroded bank of the lake (old open-pit) with outcrops of brown coal, now an information point along the educational nature trail. Photo: M. Becker (2023)

the situation during the time of mining presented in Fig. 2). The photo has been taken from a tourist viewpoint that also highlights present day gully erosion of escarpment that includes outcrops of brown coal deposit.

6. Discussion

The transformation of the natural landscape, as in the case of our study, has become inevitable due to increasing human demands (Antwi et al., 2014). Presently, determining post-mining land uses is one of the earliest and most important steps in mine closure planning (Amaro et al., 2022; Servou et al., 2023). However, this was not evident in the case of mining operations dating back to past epochs. The qualitative and quantitative assessment of landform changes caused by long-term extraction of minerals, dating back decades or centuries ago, has been the subject of research by (Wójcik, 2008; Wójcik, 2013; Raška & Kirchner, 2011; Redondo-Vega et al., 2017; Fonte et al., 2021; Machowski, 2022; Romańczukiewicz & Górniak-Zimroz, 2025). The first two studies focused on anthropogenic inversion of relief due to long-term underground mining in the Walbrzych area that was identified and quantified with descriptive statistics. Raška and Kirchner (2011) performed analyses of past events on the local landscape based on population data, old maps and aerial photographs, as well as the results of field mapping. In the next example (Redondo-Vega et al., 2017) analysed changes in land use resulting from slate, gravel and coal mining. In addition, they identified effects of mining on natural protected spaces and valuable geoheritage features. These examples also underscore the scientific and cultural significance of post-mining landscapes, as well as their potential for sustainable management and development. Studies in this domain are predominantly based on spatial and temporal analysis of landscape images developed from available historical documents and result in calculation of spatial differences between the state of the landforms prior, during and after the end of mining operations. The number of analysed time states depends on the availability of archival data. In many cases, e.g. due to high costs, loss of knowledge regarding location of mining operations, change of land ownership, there is no continuous monitoring providing data characterising the environmental conditions and their changes (Pawlik et al., 2022). However, for the analysis of the effects of mining, not so distant in time, data from open satellite missions provide suitable sources of proxy information on land use and land cover changes (DeWitt et al., 2017; Kretschmann & Nguyen, 2020; Buczyńska et al., 2023).

In our case, long-term landform transformations, and partly changes in hydrography, were best documented by the available archival materials. Analysis of this data provided for indirect

assessment of the character, area, distribution and magnitude of mining related landform transformations. We developed maps and models of the study area depicting different time states to trace, analyse, quantify and visualise development of anthropogenic landforms in the natural landscape. For this purpose, we utilised a historical GIS (HGIS) approach (Hillier & Knowles, 2008) consisting of feature overlay for mapping categorical changes and DEM of Difference for determining elevation changes that allowed us to quantify formation of mining related objects according to the date of release of cartographic and other materials. The greatest transformations in the study area were caused by the extraction of brown coal, i.e. development of open-pits, earthworks associated with mining and formation of waste heaps, and processes connected with response of the rockmass to mining from underground, e.g. development of subsidence basins. Long-term underground and open-pit mining and the subsequent reclamation processes, both planned and natural, transformed the area into a small lake-like district surrounded by forest. The observed changes, due to the geometry of the mined deposits, did not, usually, involve very large-scale modifications of natural morphological forms of the land but to a greater extent mask them or add to them. As a result, in many places, the formation of the contemporary landscape is based on complete replacement of natural landscape forms. The landform transformations observed and analysed in the studied Pustków mining field of the Babina mine, the last one to finish operation in the Muskau Arch region, are characteristic for the other parts of this region located further north and on the German side.

Detailed analysis of the post-mining landscape and thorough tracking the chronology of mining and its impacts on the surrounding environment is often constrained by the limitations in the availability of cartographic and other documentation. Therefore, it is most often performed through comparative analysis of a temporal sequence of images depicting the condition of the landscape, e.g. as in Romańczukiewicz and Górniak-Zimroz (2025) leaving gaps in between. In our study we proposed an approach consisting of complementary analyses integrating mining and topographical documents, as well as differential analysis of digital elevation models coupled with interpretations from photographic records to obtain the most complete representation of landscape transformations.

In such studies it is essential to present the results as standard, comparable metrics that studies performed in other post-mining areas can be compared to, e.g. absolute and relative values of elevation change or land transformed by mining and associated activities. Application of landscape metrics based on spatial and descriptive statistics provide quantitative values that are easy to compare between different studies. Furthermore, a standardised typology of features, applied in this study, depicting landscape

transformations in the form of representative categories such as flooded pits, waste heaps, subsidence basins, etc. should allow other studies to apply this typology and enable cross-site synthesis. The quality of HGIS based studies is related to the accuracy and precision of available materials documenting landscape (Affek, 2013). Therefore, it is essential to state uncertainty and detection thresholds in differential analyses such as those based on digital elevation models. Another limitation encountered in numerous studies is the difficulty in presenting accurately the dynamics of the observed landscape transformation processes using standard intervals, e.g. per decade, in addition to the available time stamps. Standard intervals allow cross analyses of studies that have different temporal coverage. To ensure repeatability of studies data sources should be easily identifiable and available in standard GIS formats. Finally, it is important to analyse relationships between the observed changes and the potential driving factors, e.g. mining system, direction of reclamation, time elapsed since mine closure. Apart from the feature overlay and raster map algebra functions utilised in our study, best practices in HGIS for mapping landform changes also include object-based methods for identifying discrete landforms, e.g. lakes.

Results of our study, underscore and confirm that mining activity, particularly the combined effects of underground and open-pit operations, leads to significant and measurable transformations of the original terrain. These transformations, negative such as land subsidence and open-pit formation, positive such as waste heaps or embankments, as well as land cover changes including development of anthropogenic lakes or reforestation, and other mining-related features, can be effectively quantified and analysed using historical GIS approaches and geospatial techniques, provided that adequate archival and contemporary datasets are available. Our paper builds on previous research, employing GIS to track progress of mining and expand knowledge of the anthropogenic transformations of the Muskau Arch area, with a focus on understanding its geoheritage diversity and providing interpreted information for environmental management and control.

7. Conclusions

The Muskau Arch area was shaped by complex and multiphase processes that included glaciations, combined underground and open-pit mining and reclamation. Our analysis has shown increased pressure on the natural landscape due to the progress of brown coal mining until the late 1960s. The most intensive underground mining activities occurred in the 1930s and continued until the 1960s. In the post-World War II period, open-pit mining operations intensified, peaking in activity before coming to an end in the 1970s. We estimated that approx. 37% of the study area was anthropogenically transformed. Subsequent, planned and then natural reclamation, led to the development of a unique post-mining landscape now being part of an UNESCO Global Geopark.

The application of a HGIS approach integrating various, paper and digital, data sources has proven effective for reconstructing and quantifying landscape transformations over long time scales. We have shown that GIS based analysis of historical documents allows for effective tracing of the evolution of mining despite the limitations associated with the number of available cartographic materials that covered selected years between 1903 and the present-day. In addition, the proposed approach utilising derivative DEM analysis, differential DEM processing and spatial statistics demonstrated to be useful and effective in studying the landform changes and identification of areas transformed by mining.

The assessment of the spatio-temporal evolution of anthropogenic landforms in former mining sites is important for monitoring reclamation activities and management of potential post-mining

disturbances. The statistical results and maps obtained with HGIS provide information that support these tasks. The presented methodology can serve as a model for studying other post-mining areas, provided that sufficient historical documentation and spatial datasets are available.

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