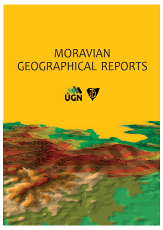

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Analysis of spatio-temporal development of mining landforms using aerial photographs: Case study from the Ostrava–Karviná mining district

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Abstract

The anthropogenic relief transformations of the mining landscape are characterised by high dynamics of changes over time that can be effectively mapped on a large scale using aerial images. The Karviná part of the Ostrava-Karviná mining district, which stands for significant hard coal mining area in the Czech Republic, has been selected to analyse the spatio-temporal development of anthropogenic landforms. Anthropogenic landforms were visually identified from the aerial images from 1947, 1966, 1971, 1985, 1994, 2009, and 2018. Specific anthropogenic landforms were analysed along with their spatio-temporal changes based on obtained vector data. The total extent and number of anthropogenic landforms increased the most during the periods 1947–1966 and 1971–1985. The same anthropogenic landforms occurred on circa 24 hectares in the entire period 1947–2018. The most anthropogenic landforms remained preserved in the last observed period 2009–2018. The multi-temporal analysis of aerial photographs and overlay operations in GIS enabled to map the age of specific landforms and to identify changed or unchanged anthropogenic landforms. This method is suitable for the study of landform dynamics at mining sites and is particularly relevant for the planning challenges in post-mining reclamation.

Keywords: *Mining landforms, aerial image, visual image interpretation, spatio-temporal changes, landforms age, Ostrava–Karviná mining district*

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1. Introduction

Landscape affected by underground hard coal mining belongs to areas with highly dynamic landscape changes. Increasing mining intensity brings dynamics into anthropogenic transformations of landforms accompanied by changes in other landscape components. Underground hard coal extraction thus has a cumulative impact on the landscape components (Lei et al., 2009). Underground hard coal mining in the landscape is primarily reflected in anthropogenic landforms. In addition to the formation of mining landforms, it can also result in planation (Dávid, 2008). This involves the use of dump material to fill in ground subsidence, for example.

In the study of a dynamically changing landscape, remote sensing data represent a significant non-generalised source of information on the state of the Earth's surface in a given moment. The spatio-temporal changes of various properties and phenomena in the landscape can also be studied more easily thanks to the higher temporal resolution of images as compared to other types of spatial data. These characteristics predetermine the use of archival aerial images in the mapping and analysis of the spatio-temporal development of anthropogenic landforms on a large scale. Moreover, in comparison with satellite images, another benefit of aerial images is a longer time period that the images cover. They can be applied in the analysis of landscape changes in areas of mineral extraction (Lausch & Herzog, 2002; Popelková & Mulková, 2018; Santo & Sánchez, 2002) and in studies focusing on mining landscape reclamation (Sklenička & Lhota, 2002).

With regard to aerial image properties and the purpose of their use in our study, visual interpretation of aerial image time series is a suitable tool to monitor the spatio-temporal changes of mining landforms, thanks to which the landforms may be inventoried and subsequently analysed their development using GIS. GIS tools can be used for mining landscape analysis even in the case of land use change assessment in relation to landforms (Ikemi, 2017). Although our study is primarily focused on the mapping of anthropogenic landforms in mining landscape, the chosen methodology will find wider application in research on the development of other Earth's surface landforms. Thus, the chosen combination of visual photointerpretation of historical aerial photographs and GIS tools can be used to monitor various long-term and short-term changes in the landscape without limitation to the Central Europe region.

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To validate the methodology, we analyse the development of mining landforms in the Karviná part of the Ostrava-Karviná Mining District (OKMD), an important area of underground hard coal mining in the Czech Republic.

The landforms and landscape structure is significantly transformed by mining anthropogenic landforms. These forms may persist in the landscape for short or long periods of time. In our study, we focused on the mapping of anthropogenic landforms from multi-temporal aerial photographs. In addition, we focused on analysing spatio-temporal changes of the landforms specifically in the period 1947–2018. Analysing spatio-temporal changes of the mining anthropogenic landforms is important both in terms of methodological advancement and its relevance for reclamation planning in mining sites. In this respect, it shows the potential and advantages of using historical aerial photographs for mapping mining landforms even in the past and for determining the age of landforms.

Our study deals with the influence of human activities on the landscape in an important area of underground hard coal mining in the Czech Republic. The following goals were set: (1) mapping the occurrence of anthropogenic landforms in the hard coal mining district in the period of 1947–2018; (2) assessing mining landforms in all years under consideration; (3) analysing spatio-temporal changes of anthropogenic landforms.

2. Theoretical background

First studies dealing with the research of anthropogenic landform changes in the Ostrava-Karviná mining district focused on convex anthropogenic landforms (Kroutilík, 1954) and since the late 1950s on the issue of tailings reclamation (Drlík, 1960, 1964; Havrlant et al., 1967; Gerlich, 1973 in Havrlant, 1980). The first scientific works focused on anthropogenic landforms in the OKMD thus arose out of the need for landscaping (Popelka, 2013). From the late 1960s onwards, Miroslav Havrlant conducted biogeographical research on the OKMD waste dumps (Havrlant, 1967), and in the late 1970s he carried out a thorough inventory of the condition and form of the dumps (Havrlant, 1980). Miroslav Havrlant mapped anthropogenic areas affected by mining extraction in the OKMD at a scale of 1:25,000 and 1:50,000. Anthropogenic landform changes in the Karviná part of the Ostrava-Karviná district were mapped by Jan Havrlant (1997a, 1997b, 1999). The author states that waste was deposited on 11 large central waste dumps, while in the 1990s most of the waste was used for reclamation purposes and was not purposefully deposited on new dumps. There were also 45 tailings ponds within the area. The size of subsidence reached up to 30 m in Karviná-Doly. The flooded area occupied 13% of the total area affected by subsidence. Other scientific projects dealt with the assessment of the state of mining landscape and options of landscape restoration (Raclavský, 2004; Stalmachová, 2004).

The Institute of Geonics of the Czech Academy of Sciences solved the issues of the decline in hard coal mining and its effect on the landscape of the Ostrava region (Martinec et al., 2003; Mikulík et al., 2004). An atlas of maps on a scale of 1:50,000 was created as a part of the project. The atlas includes maps of the impact of undermining with subsidence in the period 1961–1999, which were prepared on the basis of calculated subsidence. In some places they were compared with the actual measured values. In the Karviná part of the OKMD, 20 waste dumps and 24 tailings ponds were mapped with the state of the reclamation process indicated (Martinec et al., 2003). Mikulík et al. (2004) classified anthropogenic landforms into three main groups: convex forms, concave forms and silt fields. Within the whole OKMD, he recorded 46 waste dumps and 96 tailings pools. Martinec et al. (2006) distinguished 5 stages of development of waste dumps from fresh waste rock without atmospheric and biological effect, through two different stages of oxidation of waste dumps, to the afterburning of waste and the formation of bourn-out waste heaps. The size of subsidence in the Karviná region was estimated to be up to 40 m in places. Within the framework of this project, a map of anthropogenic landforms of the Ostrava region was prepared at a scale of 1:50,000 showing the situation as of 1988 (Mikulík et al., 2004). Zástěrová et al. (2015) focused on defining the natural conditions of waste dumps.

The knowledge of the local geological, geomorphological and hydrogeological properties of waste dumps is considered important in dealing with old burdens from mining activities. Kadlečík et al. (2015) focused on determining the extent of ground subsidence in the Karviná part of the OKMD in the Louky mining area using Differential Interferometry SAR (DInSAR) in comparison with GPS monitoring. DInSAR allows monitoring spatio-temporal changes in ground subsidence. If this method is used, it is necessary to know the extent of underground mining and changes in anthropogenic landforms. The monitoring of the development of subsidence depression using GPS methods in the Louky mining area in 2006–2010 was carried out by Doležalová et al. (2009) and Doležalová et al. (2012). The size of subsidence of the measured points ranged from less than 0.6 m to 1.7 m. Research on long-term changes in the use of the OKMD landscape in the 19th and 20th centuries was reported by Popelka et al. (2016). Mining landforms are also analysed in hard coal mining areas of neighbouring states, for example, the Ruhr District in Germany (Harnischmacher, 2007), the Upper Silesian coal mining region in southern Poland (Dulias, 2016, Szypula, 2020), and Walbrzych city in SW Poland (Jancewicz et al., 2020). Szypula (2013) statistically analysed anthropogenic line forms in the southern part of the Silesian Upland.

Statistical data and maps, including archival data, were used to investigate the impact of coal mining on the landscape of the Upper Silesian Coal Basin in Poland. Based on the input data, digital elevation models and morphometric databases were created and indicators of anthropogenic denudation were calculated (Dulias, 2016). Field research was also conducted to map contemporary geomorphological processes within selected anthropogenic landforms. In the Upper Silesian Coal Basin, direct anthropogenic landforms are found over an area of almost 150 km^2, with concave landforms outweighing convex landforms. Sandpits play the most important role, being found on more than half of the area of all post-mining landforms (Dulias, 2016). In 1993, there were 302 waste dumps in the area, covering an area of 49.2 km^2. The older ones are conical in shape. Many of the waste dumps are in the shape of massive mesas or have an irregular shape with several culminations. The largest subsidence occurred in the period 1960–1980 in connection with very intensive coal mining. Until 1991, maximum subsidence in the range of 24–28 m was recorded in Ruda Śląska (Dulias, 2016). During coal mining in the Ruhr District since the early 19th century, various mining landforms were created. The most important of them are waste dumps and mining subsidence (Harnischmacher, 2007). The earliest waste dumps were conical in shape, which later changed to an irregular or tabular (plate-like) shape. The size of subsidence ranges from a few metres to 20 m with a maximum recorded subsidence of 24 m. Modelling of subsidence in the central part of the Walbrzych (Poland) coal mine in geographic information systems with geographically weighted regression (GWR) method was also addressed by Blachowski (2016).

Geoinformation technologies that use a wide range of input data (e.g. maps, remote sensing data, DTM) extend the possibilities of the mapping of not only mining anthropogenic landforms. Ursu et al. (2011) used maps and aerial and satellite imagery to map anthropogenic landforms. The anthropogenic landforms were analysed using GIS software and subsequently a map of different types of anthropogenic influence on landforms was created. The anthropogenic landforms were also represented on a digital elevation model, which proved to be important when studying natural hazards such as hydrological modelling in floodplains.

Anthropogenic landforms in an urbanising watershed in Virginia (USA) were also analysed in their study by Chirico et al. (2021). They point out the importance of the mapping of anthropogenic landform changes using historical aerial photographs, since the knowledge of these changes provides information that is essential for land management and also hazard identification. Mandarino et al. (2021) used bibliographic research, previous researches summarisation, and photograph interpretation in a GIS environment to map anthropogenic landforms and geo-hydrological hazards of the Bisagno Stream catchment in Italy. Also, Mossa et al. (2017) used, among others, historical aerial photographs, LiDAR, and topographic maps to map anthropogenic landforms and stream channel modifications in Georgia (USA) in the context of urbanisation. Spatial and quantitative changes in anthropogenic landforms can also be determined from archival maps. Szypula (2020) used topographic and geomorphological maps from the period 1883–2014 to analyse landforms in the Upper Silesian Industrial Region in Poland at a scale of 1:50,000. Human-influenced landscapes and anthropogenic landforms in urbanised areas (Rome, Italy) were studied by Luberti and Del Monte (2020). For their research they used a multi-temporal analysis of historical and archaeological maps using GIS software. They complemented their study by examining archival documents and reports, and were thus able to uncover three millennia of landscaping related to the construction of the earliest city walls. The anthropogenic forms of the alluvial plain in north-western Italy are described in Brandolini et al. (2021). The identification and mapping of morphological changes was carried out based on the comparison of historical and contemporary maps and aerial photographs.

Another suitable information source for mapping anthropogenic landforms is LiDAR. Ninfo et al. (2016) used LiDAR data to map anthropogenic landforms in urbanised landscapes. In this way, the morphology of a multi-layered archaeological mound in the centre of Padua (Italy) could be described in detail. The research results were used for flood risk prevention and archaeological prediction. LiDAR data were also used by Waga et al. (2022) to map anthropogenic landforms in a forested landscape in Poland. They identified landforms of different ages documenting various human activities, including the remains of afforestation, expansion and modification of water structures and road infrastructure, charcoal burning and tar distillation, mineral extraction and military activity. The airborne LiDAR-based digital terrain model (DTM) was used by Jancewicz et al. (2020) to create a map of mining and industrial anthropogenic landforms in Walbrzych (Poland). Geodetic methods, including GSP methods, and satellite radar interferometry have also been used to detect mining surface deformations in the Upper Silesian Coal Basin (Dulias, 2016). Henselowsky et al. (2021) used historical maps from the first geodetic mapping in 1893, Shuttle Radar Topography Mission (SRTM)-data from 2000 and high-resolution LiDAR DEM from 2015 with 1 m pixel resolution to map landform changes and to detect anthropogenic landforms in the Rhenish mining area in Germany (open lignite mining). Around the world, measured data are also used to determine the magnitude of subsidence as a result of deep coal mining, e.g. in Indonesia (Sasaoka et. al, 2015) or China (Quanyuan et al., 2009).

3. Materials and methods

3.1 Study area

Anthropogenic landforms related to mining activities were observed in 13 cadastral areas (Fig. 1) in the Karviná (eastern) part of the Ostrava-Karviná mining district. The total area is 111.45 km^2.

The Ostrava-Karviná mining district is the chief hard coal district in the territory of the Czech Republic. It forms a southern part of the Upper Silesian Coal Basin, a larger part of which lies in neighbouring Poland (Machač & Langrová, 2003). The selected area is a typical mining region in which long-term hard coal underground mining initiated in the 1930s has had many impacts on the landscape. More significant geomorphological changes can be identified in the Karviná part of the OKMD, rather than in the region of Ostrava. Coal was extracted in 20 deep mines here, out of which two remain still active: ČSM-Sever Mine and ČSM-Jih Mine.

3.2 Data and data processing

Spatio-temporal changes of anthropogenic landforms were mapped from aerial photographs at a scale of 1:5,000. Black and white aerial images from 1947, 1966, 1971, 1985, and 1994 were provided by the Office of Military Geography and Hydrometeorology in Dobruška. The scale of the images ranged from 1:11,000 to 1:30,000. The photographs were scanned in the resolution of 600 dpi. The geometric correction was performed in the PCI Geomatica Orthoengine software (Popelková & Mulková, 2016). The RMS value reached 3 m in the case of some images, which had no effect in shifts or deformations of geometrically corrected images. Geometrically corrected images were then joined in a mosaic. For the years 2009 and 2018, we used colour orthophotos in the S-JTSK coordinate system displayed via ArcGIS Server of the State Administration of Land Surveying and Cadastre.

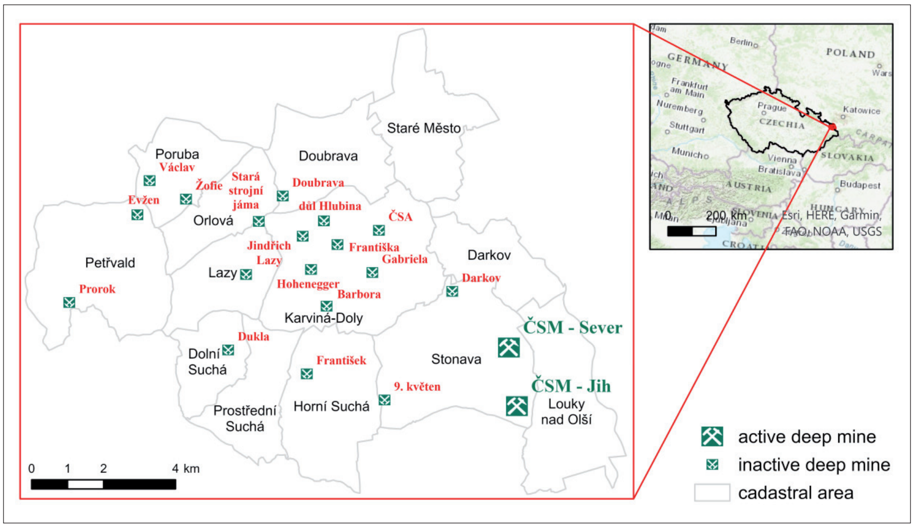

Fig. 1: Location of the study area within the Czech Republic
Source: Authors' elaboration, cadastral area from: Data ArcČR © ČÚZK, ČSÚ, ARCDATA PRAHA 2022. Basemap of software ArcGIS Pro World Topographic Map

3.3 Methods

Selected photographs and non-specific spectral signatures of individual landforms do not allow automatic image classification. Therefore, to evaluate the content of an image, standard procedures of visual interpretation were used (Jensen, 2007; Mulková & Popelková, 2013; Popelková & Mulková, 2016). We interpreted both primary displays of underground hard coal mining (waste heaps, submerged ground subsidence, tailings ponds, manipulation areas) and secondary displays (reclamation areas, communication landforms) (Mulková & Popelková, 2013). For the study area, we created a geodatabase with Feature Datasets for individual years that contained layers of landforms for each cadastral area. Created vector layers of landforms became the basis for the analytical processing of spatio-temporal development of observed landforms. Overlay operations were used to identify areas that remained unchanged as for the types of anthropogenic landforms and those that changed in the chosen period. Overlay operations also made it possible to determine the age of individual landforms, or more precisely, the observed year in which given anthropogenic landform occurs in the landscape. The processing and analysis of vector data was performed in the ArcGIS 10 software.

4. Results

The total area and number of anthropogenic landforms increased over the period of observation, with the largest increase in area between 1947 and 1966, and between 1971 and 1985 (Tab. 1). In 2018, we interpreted 382 anthropogenic landforms within 11.4% of the total study area. The largest area was represented by reclamation zones, tailings ponds, and submerged ground subsidence, occupying 77.2% of the total landform area. Anthropogenic landforms occupied the largest area in Karviná-Doly (394.29 ha; 24.1% of the cadastre area), Louky nad Olší (233.09 ha; 23.6%), Doubrava (125.18 ha; 16.1%), and Lazy (103.45 ha; 17.4%).

The position of the selected anthropogenic landforms described below in the text is shown in the Figure 2.

Name of landform	**1947**		**1966**		**1971**		**1985**		**1994**		**2009**		**2018**	
	No.	ha	No.	ha	No.	ha	No.	ha	No.	ha	No.	ha	No.	ha
Tailings ponds	22	14.02	40	136.08	41	187.75	80	430.74	96	536.32	80	379.49	94	365.72
Communication embankments	–	–	–	–	18	29.21	22	53.36	30	65.29	31	60.32	36	61.39
Manipulation areas	13	35.86	15	55.15	17	54.80	17	62.24	15	52.16	17	37.93	19	42.65
Embankments	–	–	–	–	–	–	–	–	3	4.18	3	2.90	3	3.68
Waste heaps	37	82.04	37	121.33	38	140.26	38	205.54	24	165.23	28	168.55	28	182.57
Opencast mining	5	46.88	2	33.07	2	26.59	1	7.93	–	–	–	–	–	–
Reclamation areas	–	–	–	–	3	5.50	15	74.82	15	128.75	61	372.16	58	400.32
Submerged subsidence	50	20.29	99	130.66	98	154.52	109	159.38	140	130.76	142	166.96	144	215.17
TOTAL	129	199.67	193	476.30	217	598.63	282	994.02	323	1,082.69	362	1,188.31	382	1,271.50

Tab. 1: Number of anthropogenic landforms and their total area within the whole study area in individual years. Source: Authors' calculations

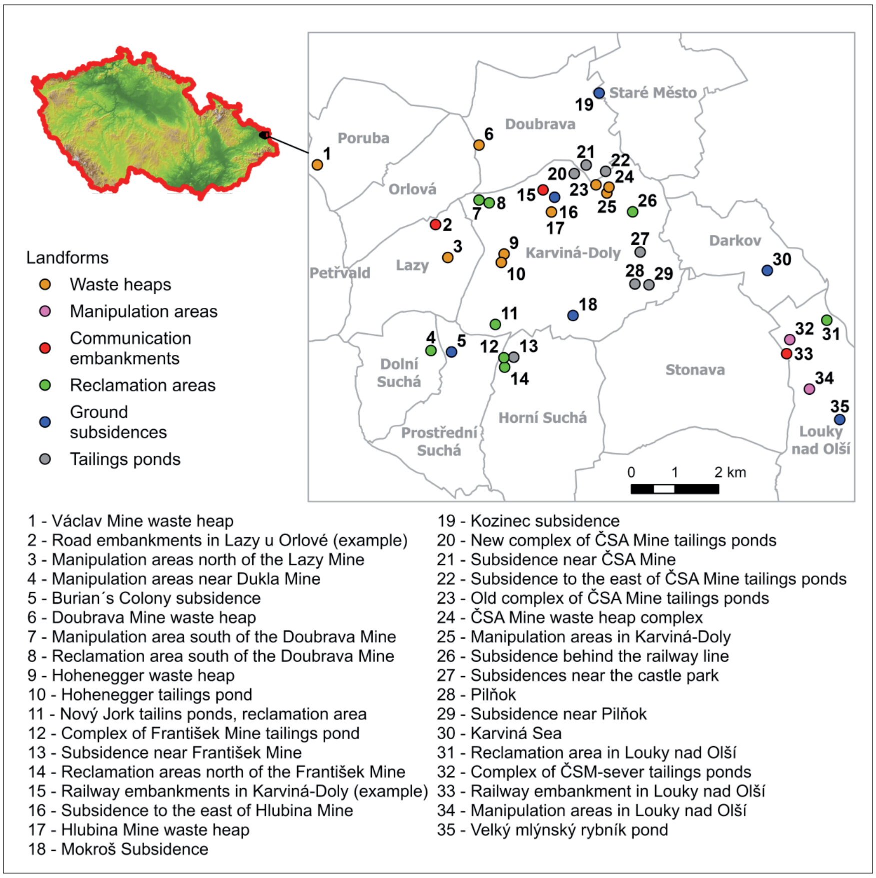

Fig. 2: The position of the selected anthropogenic landforms
Source: Authors' elaboration, cadastral area from: Data ArcČR © ČÚZK, ČSÚ, ARCDATA PRAHA 2022. Basemap of software ArcGIS Pro World Topographic Map

4.1 Development of mining landforms

4.1.1 Waste heaps

Waste heaps represent convex landforms that originate by the storage of tailings, i.e. non-recoverable waste material left over after underground extraction of hard coal. Their area can reach from a few ares to tens of hectares (Havrlant, 1980). The following types of waste heaps were mapped in the study area: waste piles, plate-shaped waste banks, terrace-like waste banks, side-hill waste heaps, ridge waste heaps, valley-fill waste heaps or their combinations. Waste heaps are usually located in the proximity of mine buildings, except for levelling heaps that are dumped in sites of sloping terrain. Active waste heaps in the photos represent vegetation-free surfaces with clearly visible contours. Over time, waste heaps become affected by natural geomorphic evolution processes (Szabó et al., 2010).

In 1947, waste heaps represented the most frequent mining landform that occupied 37.5% of the area of all anthropogenic landforms. A relatively high number of waste heaps occurred in the areas with more intensive extraction: Karviná-Doly (37.42 ha) and Lazy (11.46 ha). In 1966–2018, waste heaps occupied the largest area in Karviná-Doly and Doubrava. Increasing mining intensity affected the area of waste heaps up to the year 1985. From 1985 to 1994 the area of waste heaps decreased (Tab.1). A slight increase was identified in 2009 and 2018. In connection with the increasing occurrence of submerged ground subsidence and tailings ponds in 1966, and since 2009 also due to an increase in reclamation areas, waste heaps no longer belonged to dominant anthropogenic landforms of the study area.

The vastest waste heaps in the whole area of interest in 1947–1971 was the waste heap of the Doubrava Mine, the maximum area of which was 24 ha (Tab. 2). A side-hill waste heap was accumulated in a depression with the elevation difference of 20 m towards the surrounding terrain; its northern part is of a terrace-like character (Havrlant, 1980). In 1994, the western part of this waste heap became covered by self-seeding plants, while the eastern part remained devoid of vegetation. In 2009, amusement Dinopark was established in the eastern part of the waste heap body. The western part is largely covered by a forest, while the remaining area is grassy.

Since 1985, the largest waste heap (34.97 ha) in the study area has been the heap of the Hohenegger Mine (Fig. 3). In 1971 and 1985, it was constituted by a relatively complex body in a form of a table-like heap with significant terraces in its northern part. As a result, there was a distinctive formation in the landscape of the elevation difference of c. 25 m (Havrlant, 1980). By 1994, the area increased to 49.93 ha. The top part of the waste heap has been reclaimed to arable land. There is also an airfield for modellers. The planting of trees is visible on the slopes.

The third largest waste heap of the study area in 1966 and 1971 was the heap (11 ha) of the Václav Mine in Poruba. In its northern part, it is a prolonged ridge, whereas the southern part was disrupted by waste rock removal and new heaping up (Havrlant, 1980). The elevation difference, as compared to the surrounding terrain, is more than 20 m. At present, the heap is forested.

Another relatively large waste heap complex worth mentioning is to the north of the ČSA Mine in Karviná-Doly. In 1966, it was constituted by a heap-like unit or a table-like unit. Since 1985 it has been the second largest waste heap complex. In 2018, it was formed by 4 units. The south-eastern part was partly reclaimed as a result of tree planting on the slopes of the heap. The complex is mainly a table with irregular heap peaks covered by smaller heaps or tables.

4.1.2 Submerged ground subsidence

Ground subsidence originates as a result of the surface subsidence above the mined-out space. The size depends on geological conditions, tectonics, and the area and thickness of coal seams (Havrlant, 1980). The subsidence can be filled with water. In the aerial images, only submerged ground subsidence can be easily identified. In comparison with other water surfaces, submerged ground subsidence usually has an irregular broken shape that is given by relief formation at the site of flooding. In most cases, the shape and area of submerged ground subsidence are subject to temporal changes due to ongoing surface subsidence.

Waste heap	**Area (ha)**						
	1947	1966	1971	1985	1994	2009	2018
Doubrava Mine waste heap	12.62	24.09	24.30	23.82	23.11	23.59	23.59
Hlubina Mine waste heap	6.57	–	–	–	–	–	–
Hohenegger waste heap	5.66	16.66	19.54	34.97	49.92	49.92	49.92
Václav Mine waste heap	3.91	11.29	11.00	10.92	5.58	5.58	5.58
ČSA Mine waste heap complex	5.53	12.54	16.85	34.38	36.93	35.83	38.75

Tab. 2: Area of the largest waste heaps in individual years. Source: Authors' calculations

Fig. 3: Hohenegger waste heap in aerial photos from 1971 and 2018
Sources: The photo was provided by the Military Geography and Hydrometeorology Office in Dobruška. © MO ČR/GeoSI AČR. Orthophoto (2018), map services of ČÚZK (State Administration of Land Surveying and Cadastre)

Aerial images of 1947 revealed 50 areas of submerged ground subsidence (10.2% of all anthropogenic landforms). The largest areas of the submerged ground subsidence were in Karviná-Doly (13.66 ha), Doubrava (5.63 ha), and Horní Suchá (2.12 ha). The very largest submerged ground subsidence (3.27 ha) was found in Doubrava, to the north of the ČSA Mine (Tab. 3).

The images of 1966 showed a significant increase in submerged ground subsidence that comprised 27.4% of all anthropogenic landforms within the study area (Tab. 1). The total area of the subsidence continued to grow by 1985. However, its share in the total area of anthropogenic landforms decreased to 16.0%. After a decrease in the area of submerged ground subsidence identified from images of 1994, there was a renewed increase of the area. In 2018 submerged ground subsidence constituted 16.9% of all anthropogenic landforms.

Based on the images of 1994, the territory most affected by undermining and subsequent flooding of ground subsidence was that of Karviná-Doly. In 1971, there was 63.9% of all submerged ground subsidence that occupied 98.80 ha. Towards the year 1994, the area decreased to 39.08 ha. Another significant occurrence of submerged ground subsidence was mapped in 1966 in Horní Suchá (15.62 ha) and Prostřední Suchá (11.67 ha) and in 1971 also in Lazy (12.50 ha). These were newly identified in 1985 in Darkov (8.45 ha) and in Louky nad Olší (14.05 ha), whereas their area continued to increase in the following years. In 2009 and 2018, these are the areas where undermining was most manifested by the creation of submerged ground subsidence. In 2018, the largest areas were revealed in Darkov (44.27 ha), Louky nad Olší (40.37 ha), and Doubrava (39.45 ha).

In 1966, the largest submerged ground subsidence was found near the present-day Pilňok tailings pond in the south-eastern part of Karviná-Doly (Tab. 3). The second largest submerged ground subsidence was located to the north of the František Mine in Horní Suchá. A vast territory of 11 submerged ground subsidence areas (22.85 ha) was identified to the southeast of the ČSA Mine, namely at the place where there used to be sports complexes and a castle park in 1947. In 1971, the devastating effects of undermining were also connected to the area expansion of this submerged ground subsidence. Four other areas of submerged ground subsidence were found to the north of this complex, behind the railway line, with the area of 11.82 ha. By 1971, this area decreased due to filling the basins with tailings.

In 1985, the largest submerged ground subsidence was found to the east of the surface constructions of the Dukla Mine, at the place of Burian's Colony along the borderline of Dolní Suchá and Prostřední Suchá. Next in the ranking was the submerged ground subsidence at the place of a former castle park in Karviná-Doly and to the east of tailings ponds of the ČSA Mine on the border of Karviná-Doly and Doubrava.

In 1994, the largest submerged ground subsidence was Mokroš in Karviná-Doly, to the southeast of the Barbora Mine. It was followed by the submerged ground subsidence at the site of Burian's Colony, and in Darkov, at the site of nowadays Karviná Sea (Fig. 4). The area of the Karviná Sea increased to 33.30 ha in 2018. In 2009, it was the largest submerged ground subsidence. The second largest submerged ground subsidence in 2009 was the former pond named Velký mlýnský rybník in Louky nad Olší (18.38 ha). New submerged ground subsidence originated on the border of Doubrava and Staré Město in the locality of Kozinec. Along with the neighbouring submerged ground subsidence, the total area of submerged ground subsidence Kozinec was 47.17 ha in 2018.

Subsidence	Area (ha)						
	1947	1966	1971	1985	1994	2009	2018
Subsidence near ČSA Mine	3.27	–	–	–	–	–	–
Subsidence near František Mine	1.51	14.28	–	–	–	–	–
Subsidence to the east of Hlubina Mine	2.81	–	–	–	–	–	–
Subsidence near Pilňok	0.00	15.60	21.10	–	–	–	–
Subsidence near the castle park	1.22	22.85	42.93	14.93	–	–	–
Subsidence behind the railway line (Karviná-Doly)	0.25	11.82	6.29	4.75	0.58	0.33	0.35
Burian's Colony subsidence	–	3.68	7.81	17.05	12.18	5.20	5.87
Subsidence to the east of ČSA Mine tailings ponds	–	2.10	3.84	9.46	–	–	–
Mokroš subsidence	1.28	5.09	–	–	10.29	9.87	10.25
Karviná Sea	–	–	–	–	7.93	31.28	33.30
Velký mlýnský rybník pond	–	–	–	–	5.77	18.38	21.16
Kozinec subsidence	–	–	–	–	–	15.23	47.17

Tab. 3: Area of the largest submerged ground subsidence. Source: Authors' calculations

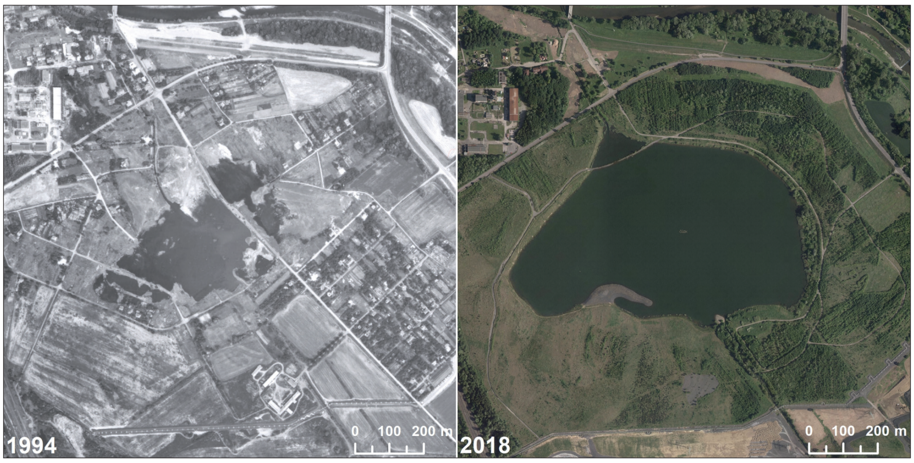

Fig. 4: Karviná Sea in aerial photos from 1994 and 2018
Sources: The photo was provided by the Military Geography and Hydrometeorology Office in Dobruška. © MO ČR/GeoSI AČR. Orthophoto (2018), map services of ČÚZK (State Administration of Land Surveying and Cadastre)

4.1.3 Tailings ponds

Tailings ponds are used for permanent or temporary storage of hydraulically transported tailings (Kirchner & Smolová, 2010). They are either artificially created, or they are already existing water areas such as submerged ground subsidence. Unlike submerged ground subsidence, tailings ponds usually have a regular geometrical shape. They are found close to surface constructions of mines. In aerial photos, we observe well visible embankments in the vicinity of many tailings ponds. The aerial images also show dry tailings ponds in cases where the service life of tailings ponds has ended. These dry tailings ponds are shallow concave landform shapes filled with tailings that are gradually reclaimed, or they become overgrown with airborne vegetation.

In the study area, tailings ponds are large anthropogenic landforms. The smallest area covered by tailings ponds was recorded within the study area in 1947 (Tab. 1). The largest system of tailings ponds originated to the north of ČSA Mine at the place of today's waste heap and on the top of the Hohenegger waste heap. From 1947 to 1994, the area of tailings ponds increased rapidly. The largest extent was mapped in 1994 when a total of 96 tailings ponds occupied 49.5% of the area of all anthropogenic landforms. By 2018, following the decline in coal mining and subsequent reclamations, the extent of tailings ponds dropped. The highest number of tailings ponds was observed in Karviná-Doly with the maximum number in 1994 (218.1 ha). In Louky nad Olší, tailings ponds appeared in aerial images as late as 1985. It is the area with the second highest representation of tailings ponds in 1994 when their extent reached its maximum (86.04 ha). In Doubrava, tailings ponds appear in images starting in 1966 with the maximum area in 1994 (51.86 ha).

In 1966, the largest tailings ponds complex was found to the north of the ČSA Mine in Karviná-Doly. The maximum extent of this complex was recorded in 1994 (Tab. 4). In 1994, two largest tailings ponds were identified in Karviná-Doly. The first one formed a part of a complex of three tailings ponds in the Pilňok locality which had contained submerged ground subsidence by 1971. The extent of the largest Pilňok tailings pond was 54.16 ha. The second largest tailings pond was Nový Jork to the southwest of the Barbora Mine. Both of these localities were first captured in the aerial images of 1985. By 2018, the extent of tailings ponds in both localities had decreased due to reclamation activities (Tab. 4).

From 1985, the second largest complex of tailings ponds was found to the east of the ČSM-Sever Mine (Fig. 5). In 1994, this complex comprised five tailings ponds of maximum area 96.44 ha. In 2018, the complex contained 13 tailings ponds with the total area 80.89 ha, out of which 25 ha was reclaimed.

4.1.4 Manipulation areas

Manipulation area is a type of complex surface created by convex and concave shapes of various dimensions and typically containing unpaved roads. Manipulation areas are generally found in the proximity of mine buildings, tailings ponds, or waste heaps where they perform the service and transport functions. Manipulation areas demonstrated the least extent in 1947. From this year onwards, it went increasing, reaching its maximum in 1985 (Tab. 1). In 1947, the largest manipulation areas were those in Dolní Suchá (13.82 ha). They were connected to the surface buildings of the Dukla Mine in the east. In 1966, 1971, 1985, and 2009, manipulation areas were the largest in Karviná-Doly, with the maximum in 1966 (31.01 ha). There, the very largest manipulation area was to the south of the Doubrava Mine (7.37 ha). In 1994, the largest number of manipulation areas in Lazy (14.18 ha) north of the Lazy Mine was mapped. In 2018, most manipulation areas were found in Louky nad Olší, and they covered the area of 15.33 ha to the east of ČSM-Sever and ČSM-Jih Mines, in the vicinity of tailings ponds and Bohumín-Čadca railway line.

Tailings ponds	**Area (ha)**						
	1947	1966	1971	1985	1994	2009	2018
Old complex of ČSA Mine tailings ponds	4.71	4.49	1.64	–	–	–	–
Hohenegger tailings pond	4.19	–	–	–	–	–	–
New complex of ČSA Mine tailings ponds	–	74.54	86.21	110.87	115.55	94.51	95.71
Pilňok	–	–	–	49.55	66.28	38.61	38.09
Nový Jork	–	–	–	29.53	32.64	7.93	5.65
Complex of František Mine tailings pond	–	10.72	43.08	61.09	63.77	30.76	29.72
Complex of ČSM-Sever tailings ponds	–	–	–	75.93	96.44	88.35	80.89

Tab. 4: Areas of the largest tailings ponds
Source: Authors' calculations

Fig. 5: Complex of ČSM-Sever tailings ponds in aerial photos from 1994 and 2018
Sources: The photo was provided by the Military Geography and Hydrometeorology Office in Dobruška (© MO ČR/GeoSI AČR), Orthophoto (2018), map services of ČÚZK (State Administration of Land Surveying and Cadastre)

4.1.5 Reclamation areas

Reclamation areas are convex landforms that resemble low flat waste heaps. They originate as a part of reclamation buildings. Unlike waste heaps, they can be found quite far from mine surface buildings. Visual interpretation requires support data to differentiate reclamation areas from waste heaps. Reclamation areas were first identified in images from 1971 in Karviná-Doly and Horní Suchá that originated to level subsided terrain. The size of reclamation areas increased by 2018 with a slightly more significant increase in 2009 when 61 reclamation areas occupied 31.3% of the total area of all anthropogenic landforms (Tab. 1). In 2009, reclamation areas were most expanded in Karviná-Doly (87.36 ha), Louky nad Olší (78.36 ha) and Horní Suchá (44.52 ha). The larger ones were observed in Karviná-Doly, at the place of tailings ponds to the west of the Barbora Mine in the locality of Nový Jork (28.41 ha), and to the south of the Doubrava Mine, at the place of former tailings ponds (42.55 ha). In Louky nad Olší, a vast reclamation area was mapped to the east of the ČSM-Sever Mine with an overlap to Darkov (Fig. 6). Ten reclamation areas were recorded on the area of 84.71 ha at a place of a subsided locality. In Horní Suchá, the reclamation concerned tailings ponds and submerged ground subsidence to the north of the František Mine.

In 2018, reclamation areas belonged to the largest anthropogenic landforms occupying 31.5% of the area of all anthropogenic landforms. The largest reclamation area was in Louky nad Olší (90.58 ha), where reclamation took place to the east of the ČSM-Sever Mine.

Fig. 6: Reclamation areas to the east of the ČSM-Sever Mine in aerial photos from 2009 and 2018
Source: Map services of ČÚZK (State Administration of Land Surveying and Cadastre)

4.1.6 Communication landforms

Communication landforms, which were created as a result of deep mining, were visually interpreted from aerial images. In such a case, they serve to level subsidence destroying roads. Communication landforms are convex line landforms of sometimes even a few metres in height. The following landforms were distinguished: railway embankments, road embankments, and embankments of engineering networks. Communication landforms were first observed in images from 1971. Their size increased by 1994 (Tab. 1). They were railway embankments of the original Košice-Bohumín railway and rail sidings leading to mines, embankments on Ostrava-Karviná road or Orlová-Havířov road.

In 1971, 69.5% (20.29 ha) of all communication landforms within the study area was related to Karviná-Doly followed by Louky nad Olší (3.35 ha) and Lazy (2.17 ha). The size of communication landforms within these cadastral areas remains the largest in the whole study area as late as 2018. In 2018, communication landforms covered 24.11 ha in Karviná-Doly, 17.6 ha in Louky nad Olší, and 10.69 ha in Lazy. The mapping of these landforms comprised mainly railway embankments under rail sidings leading to mines and those on Bohumín-Čadca railway No. 320, namely in Louky nad Olší, where there are two largest embankments of 17.16 ha.

4.2 Analysis of spatio-temporal changes of anthropogenic landforms

We used analytical tools of GIS software to identify areas where anthropogenic landforms remained unchanged in a selected period. It was thus possible to determine the age of landforms within the studied period (Fig. 7). It is not possible to determine from Figure 7 what type of anthropogenic landform is found in specific parts of the locality. The age of individual landforms is shown in the Figure 8 on the example of the Lazy cadastral area. Total areas containing identical anthropogenic landforms between individual time intervals of the study period of 1947–2018 are given in Table 5.

In the observed period 1947–2018, identical anthropogenic landforms occur only on less than 24 ha. Those preserved most were waste heaps (22.73 ha). Most waste heaps were preserved at the boundary of Orlová and Doubrava (6 ha) and Karviná-Doly (5 ha). The total area of preserved submerged ground subsidence was just 1.08 ha. From 1966 to 2018, the preserved landforms included 80.67 ha of tailings ponds, 35.54 ha of waste heaps, 11.73 ha of submerged ground subsidence, and 1.67 ha of manipulation areas. The vastest tailings ponds (53 ha) remained preserved north of the ČSA Mine. Other largest areas preserved from 1966 comprise: a waste heap in Doubrava (9.80 ha) and tailings ponds in Prostřední Suchá (9.51 ha).

From 1971 to 2018, the most preserved landforms were waste heaps (26.60 ha), tailings ponds (23.82 ha) and communication landforms (18.24 ha). Lower figures are observed in connection with submerged ground subsidence (5.06 ha). The system of

Identical anthropogenic landform	**Area**		
	(ha)	(% total area)	(% landforms)
From 1947 to 2018	23.81	0.21	1.45
From 1966 to 2018	129.61	1.16	7.89
From 1971 to 2018	74.37	0.67	4.53
From 1985 to 2018	283.43	2.54	17.25
From 1994 to 2018	232.66	2.09	14.16
From 2009 to 2018	381.12	3.42	23.20

Tab. 5: Total areas of an identical anthropogenic landform in the period 1947–2018
Source: Authors' calculations

tailings ponds north of the ČSA Mine expanded since 1971 by additional areas with a total area of 9.57 ha. The above-mentioned tailings ponds in Prostřední Suchá were enlarged by 6.68 ha. The third largest anthropogenic landform preserved from 1971 to 2018 was an embankment in Karviná-Doly (5.99 ha).

When we disregard the last short time interval (2009–2018), most anthropogenic landforms were preserved from 1985. More than half of their extent is occupied by tailings ponds (155.77 ha) and less than a third of waste heaps (49.06 ha). These are followed by reclamation areas (31.61 ha), communication landforms (27.33 ha)

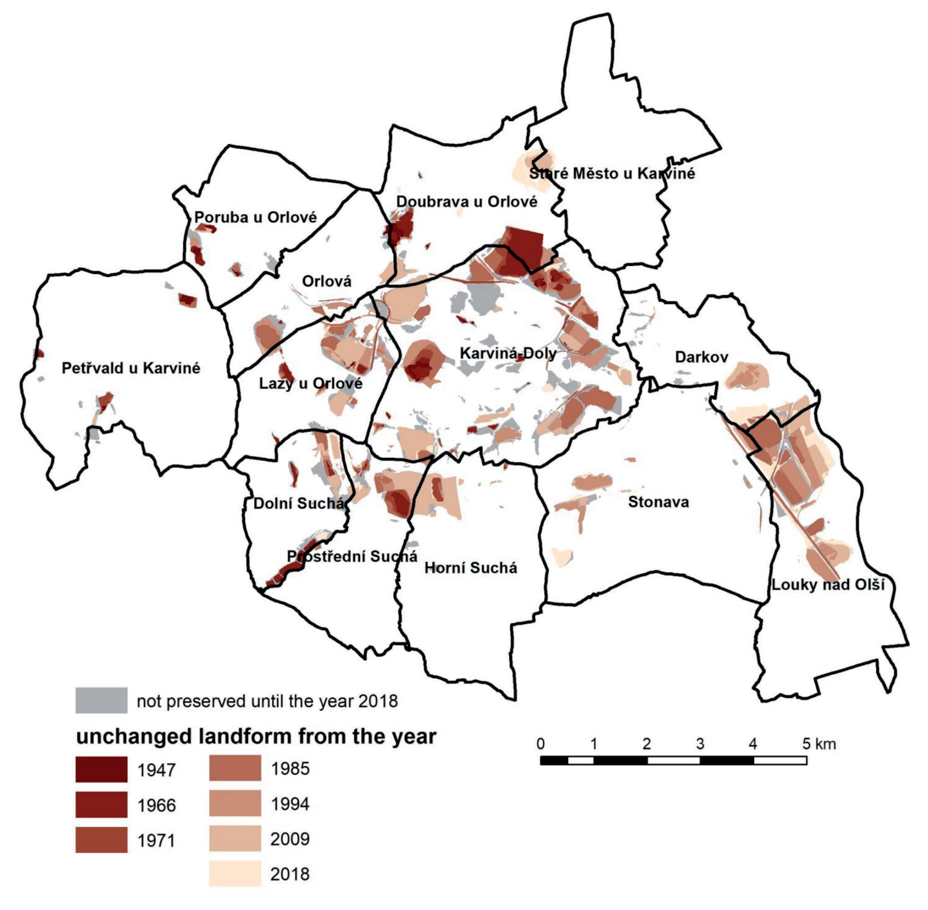

Fig. 7: The unchanged mining landforms within period 1947–2018 in Ostrava-Karviná mining district
Sources: Authors' elaboration, cadastral area from: Data ArcČR © ČÚZK, ČSÚ, ARCDATA PRAHA 2022

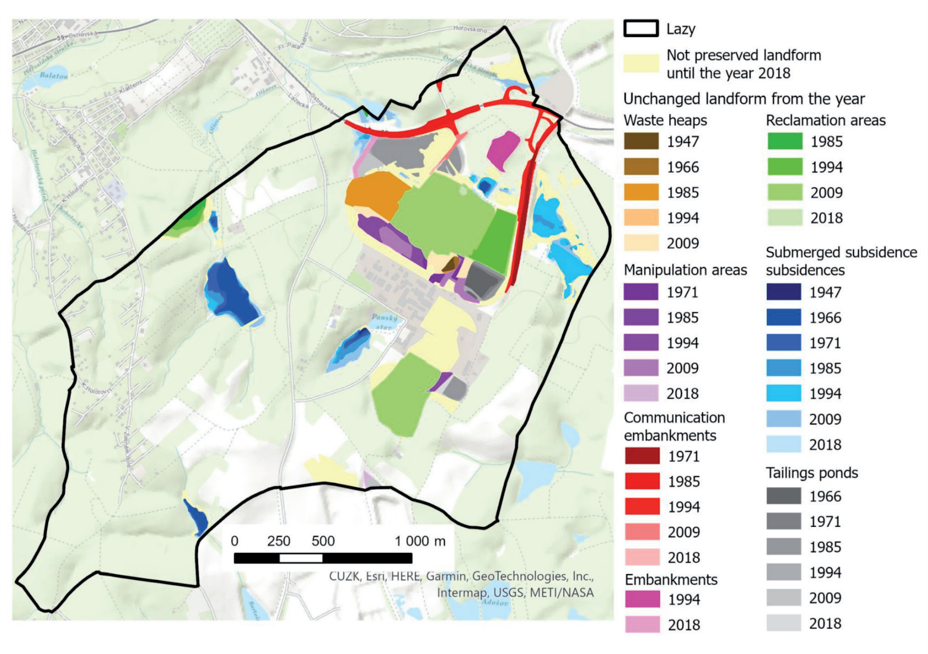

Fig. 8: The unchanged anthropogenic landforms in Lazy
Sources: Authors' elaboration, cadastral area of Lazy from: Data ArcČR © ČÚZK, ČSÚ, ARCDATA PRAHA 2022. Basemap of software ArcGIS Pro World Topographic Map

and submerged ground subsidence (19.31 ha). The vastest group of tailings ponds occurs north of Louky nad Olší (39.73 ha). Next come two tailings ponds parallel to each other in Karviná-Doly (34.11 ha), a tailings pond in Louky nad Olší (15.58 ha) and a reclamation area in Orlová (15.01 ha).

Some submerged ground subsidence turned into tailings ponds in the following observed period. In each period of those from 1947 to 1994, this represents the largest difference in connection with the studied anthropogenic landforms. For example, 8.55 ha of submerged ground subsidence from 1947 were used as tailings ponds in 1966; in the following periods, this change has a growing trend: 23.38 ha (1966–1971) and 48.79 ha (1971–1985). Most submerged ground subsidence (50.72 ha) turned into tailings ponds in 1985–1994.

From 1985, changes in anthropogenic landforms from reclamation dominated. The most significant change in all studied periods is the transformation of 105.36 ha of tailings ponds into reclamation areas in 1994–2009. The same change, yet to a smaller extent (12.51 ha), dominates the period 2009–2018. Submerged ground subsidence was reclaimed as well: 16.81 ha in 1971–1985, 14.93 ha in 1985–1994, and 11.44 ha in 1994–2009. Reclamation also took place in areas of mineral extraction and in manipulation areas. Another frequent change was using original manipulation areas as waste heaps, predominantly on 18.04 ha in 1985–1994.

5. Discussion

5.1 Landform dynamics

The analysis of spatio-temporal development of mining landforms using the photointerpretation of aerial images is a suitable tool in capturing the dynamics of such landforms in a quickly transforming mining landscape. The changes in these anthropogenic landforms are related to the main driving force in the study area – industrialisation. Industrialisation, which started to form the structure of the Karviná landscape in the 1850s, was further reinforced by the political development of former Czechoslovakia after 1948. Newly emerging mining anthropogenic landforms that significantly transform the relief and the landscape structure persist in the landscape for either a short or long period. The longest persisting mining landforms are related to mineral extraction (Migoń & Latocha, 2017).

The most distinctive convex landforms in the mining landscape are waste heaps. In 1947, waste heaps occupied more than a third of all anthropogenic landforms in the study area. In 1971, waste heaps were located on 1.26% of the total area, whereas in the Ruhr District their proportion is only 0.02% (Harnischmacher, 2007). The total extent of waste heaps increased by 1985 in connection with increasing mining activities. Mineral extraction reached its peak between 1979 and 1985, with the extraction volume exceeding 16 million tons of hard coal per year (Martinec et al., 2006). The vastest waste heap area was identified in Karviná-Doly, Doubrava and Lazy. The increased emergence of waste heaps was also reflected by primary evidence of heaps in 1956 (Popelka, 2013), with the biggest concentration of tailings heaps occurring in Karviná-Doly. The spatio-temporal analysis shows that the most preserved landforms in the studied period of 1947–2018 were waste heaps. However, some waste heaps ceased to exist due to tailings extraction for the construction of roads and dam barriers and regulation of the waters (Drlík, 1964). Since the 1960s, tailings were gradually more and more used for large-scale filling of ground subsidence within targeted reclamation processes. Therefore, the extent of waste heaps identified in aerial images after 1985 decreased accordingly. The share of waste heaps in the total area decreased from 1.84% in 1985 to 1.48% in 1994. Compared to the Polish part of the Upper Silesian Coal Basin, where this share was 0.91% in 1993 (Dulias, 2016), the representation of waste heaps in the area of interest is higher. In 2018, waste heaps were located on 1.64% of the total area, while in Walbrzych their share was 3.05%.

A typical display of deep mining is ground subsidence. Terrain movements cause grave damage to buildings, infrastructure and soils, and in the case of vast subsidence, as in the Karviná region, they can lead to significant territory devastation. The total area of ground subsidence from the beginning of the mining activities cannot be specified scientifically due to the lack of systematic observation until 1960. The maximum total subsidence in the Karviná region is estimated at 40 metres in depth. Long-term and strong subsidence affected, for instance, the Church of St. Peter from Alcantara in Karviná (which subsided by almost 33 metres from 1950), or the building of the railway station in Karviná-Doly (which subsided by 30 metres from the beginning of the 1970s to the mid-1990s) (Havrlant, 1997b).

Submerged ground subsidence was recorded in the study area as early as 1947, and their total extent went increasing up to the present time. By 1994, submerged ground subsidence was most prevalent in Karviná-Doly. In 2018, they were of the largest area in Darkov, Louky nad Olší and Doubrava. Some submerged ground subsidence was used in tailings management from the second half of the 20th century (Havrlant, 1980). These dynamic changes can be documented by the spatio-temporal analysis of aerial photographs of 1947–1994, with the highest increase between 1985 and 1994.

Tailings ponds in the Karviná Region appeared largely as late as in the second half of the 20th century in connection with the development of hard coal treatment technology as in the 1950s a problem arose regarding a large amount of fine-grained waste. During the following decades (up to 1994), the area of tailings ponds increased rapidly. Towards the year 2018, however, their area decreased due to a gradual decline of mining, changes in the coal treatment technology and reclamation activities. Most tailings ponds were mapped in Karviná-Doly, Louky nad Olší and Doubrava, with the maximum in 1994.

From the 1990s, the tailings ponds were gradually mined, mainly for energy purposes. The disappearance of tailings ponds as a result of reclamation with a maximum in the period 1994–2009 and then in 2009–2018 is also confirmed by the analysis of aerial photos. Afterwards, biologically precious wetlands and bodies of water formed in the place of reclaimed tailings ponds (Hlavatá et al., 2012). In 2018, the share of tailings ponds in the total area was 3.28%. Of these, 1.98% were water-filled tailings ponds. In Walbrzych, the share of tailings ponds was 0.71% of the total area (Jancewicz et al., 2020).

The formation of submerged ground subsidence and tailings ponds leads to an increase of water areas in the mining landscape. This phenomenon is described by Rzętała and Jaguś (2012) in the Upper Silesian region and surrounding areas. The Upper Silesian Anthropogenic Lake District (6,766 km^2) consists of 4,773 water bodies of various origins, including submerged ground subsidence. The lake density of the Lake District is 2.74%. In Karviná part of OKMD, the lake density was 3.71% in 2018. The area of submerged ground subsidence and tailings ponds was included. Other water areas were not considered. The area of manipulation areas increased due to increasing mining up to 1985, and then it started to decrease after 2009.

Reclamation areas and communication embankments started to appear in the study area in 1971. Efforts to reclaim the landscape affected by mining made it possible for reclamation areas to enlarge up to the last studied year. The extent of communication embankments increased by 1994. Most communication embankments, manipulation areas and reclamations areas were identified in Karviná-Doly. If we focused on communication embankments as line forms and if we observed other linear anthropogenic landforms, it would be interesting to statistically evaluate the data and compare them with the results of Szypula (2013) in the southern part of the Silesian Upland.

In 2018, the share of anthropogenic landforms was 11.41% of the total area in the Karviná part of OKMD. This value is higher than in the Polish part of the Upper Silesian Coal Basin, where anthropogenic landforms were located on 2.78% of the total area, i.e. almost 150 km^2 (Dulias, 2016). However, this proportion is comparable to the proportion of man-made landforms in Walbrzych, which is 12% of the entire coal mining zone area (Jancewicz et al., 2020).

5.2 Study limitations

Although aerial images represent a valuable source of information on the state of landscape at the time of aerial photography, it is necessary to consider input data when assessing the occurrence and development of anthropogenic landforms. Our analysis was based on aerial photos from eight observed years to capture the real state as much as possible. Some results can be distorted because of different intervals between individual data sets. We observed six periods: 1947–1966 (19 years), 1966–1971 (5 years), 1971–1985 (14 years), 1985–1994 (9 years), 1994–2009 (15 years) and 2009–2018 (9 years). The total extent and number of anthropogenic landforms increased the most in the long periods 1947–1966 and 1971–1985 (Tab. 2). The third longest period (1994–2009) was characterised by a decline in mining intensity. In the case of mining landscape, it is, therefore, more convenient to shorten time intervals in the period of intensive mining if it is allowed by the availability of aerial photographs.

Another limitation rests in the study of the flooding of subsided terrain followed by the occurrence of submerged ground subsidence, which, unlike dry subsidence, can visually be interpreted from aerial photographs. On the one hand, dry subsidence can be identified based on indirect photointerpretation signs such as the demolition of buildings, the devastation of agricultural areas, or changes in the road structure. However, we can hardly determine the size of dry subsidence due to missing elevation data. A necessary tool is a digital terrain model that would have to be made in the time of aerial photography to capture the current elevation conditions of the study area. To monitor the size of mining subsidence, we can use geodetic methods, differential InSAR (DInSAR) technique (Raucoules et al., 2003), GPS technique (Doležalová et al., 2009), a combination of GPS and DInSAR (Kadlečík et al., 2015) or GIS-based multi-factorial weighted spatial regression (Blachowski, 2016). Nevertheless, these methods can barely be applied retrospectively to determine the size of subsidence in the past.

6. Conclusion

Historical aerial photographs are a valuable source of information on the state of the landscape. An indisputable advantage of multi-temporal aerial photography is the possibility to make spatio-temporal analyses that capture the changes in individual landforms. Although previous studies performed terrain mapping of anthropogenic landforms in the study area, the assessment of landform development and age has so far not been conducted. The total extent and number of anthropogenic landforms in the study area increased the most in the periods 1947–1966 and 1971–1985. The largest area (1,271.5 ha) and number (382) of mining landforms was identified in 2018. The largest area was occupied by reclamation zones, tailings ponds, and submerged ground subsidence.

When studying the same type of anthropogenic landforms in our study, we found that these occurred on c. 24 ha in the entire study period 1947–2018. Waste heaps were the most preserved landforms in the studied period of 1947–2018. Submerged ground subsidence and tailings ponds showed a high dynamic of changes. In 2018, reclamation areas had the largest area. They were first detected in images from 1971. Most anthropogenic landforms (381 ha) remained preserved in the last observed period 2009–2018. In comparison with field mapping, visual interpretation may be performed in a relatively shorter time concerning the size of the study area. In this case, we can also ensure higher accuracy when determining the extent of individual landforms. Besides being an experienced interpreter, it is often necessary to be acquainted with the territory. It is desirable to use support resources to identify disputed objects in an image.

If we compare visual photointerpretation with the automatic image classification of the remote sensing method, a drawback is time demands. It is, however, a method that cannot effectively be substituted with digital image classification in the case of mapping mining landforms from historical aerial photographs. Apart from the information on the state of the landscape in a given year, data acquired by visual photointerpretation bring a potential for the analysis of spatio-temporal changes of anthropogenic landforms.

The study employs an interdisciplinary approach, utilising remote sensing data and geographic information systems tools in the field of anthropogenic geomorphology to monitor the status and historical evolution of anthropogenic landforms. This approach represents a synthesis of geomorphological mapping and geoinformatics, with necessary overlaps to other disciplines, such as historical geography and landscape ecology. The findings of the study are of interest not only to geomorphologists and landscape ecologists, but also to geoinformaticians, historians, geomorphologists and specialists engaged in spatial and landscape planning. Understanding landform dynamics provides key application in the reclamation of post-mining landscapes, where information on landforms stability and their suitability to enhance landscape structure and functions poses an essential challenge for consequent planning phases.

The study is also useful for comparison with the evolution of anthropogenic landforms in other areas affected by deep mining not only in Europe but also in non-European mining areas. Another research direction is to map spatio-temporal changes of anthropogenic landforms in the emerging post-mining landscape, complemented by morphometric analyses of anthropogenic landforms.

Acknowledgement

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