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Original Research

Environmental Burdens in Central Spiš Region, Slovakia

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Abstract

Anthropogenic geomorphology focuses on the study of man-made landforms and the processes that contributed to their creation. It also examines the processes that impact these relief forms in the landscape after the activities that formed them have ceased. The original natural structure of the landscape was significantly shaped by human activities. The Central Spiš region has suffered significant damage due to mining and industrial activities. Following the decline of mining, the abandoned mining and industrial sites in this area were left to the natural processes of recovery. However, natural forces have not been enough for this, and so the region has remained without a chance to attract investors and achieve ecological stability. Localities and objects related to mining and industrial activity today represent environmental burdens in the original natural landscape. They need to be eliminated as soon as possible for the greening of the landscape and the health of its inhabitants. The main research problem is the unknown state of abandoned anthropogenic landforms, their unknown composition, and the lack of information for landscape management with the aim of restoration. The aim is to obtain detailed information about the opening and dimensions of the largest anthropogenic landforms in the region, their heavy metal content, and the potential danger they may pose. In conclusion, we present the possibilities of environmental protection. The studied anthropogenic landforms have proven to be significantly different and require a differentiated approach to solving the issue of restoration of a man-made landscape.

Keywords: geomorphology, man-made landforms, photogrammetry, digital relief models, environmental burdens

Introduction

Based on field research, we conclude that the region of Central Spiš in Slovakia represents a landscape marked by mining and industrial activities that have been taking place here for centuries and have left indelible traces in the landscape. The most significant features include anthropogenic relief forms that originate from mining and industrial activities. These sites are remnants of the past but currently represent environmental burdens with a dangerous impact on the landscape.

The southeastern part of the Spišská Nová Ves district with a small overlap into the Gelnica district was selected as the research location (Fig. 1). Many mining and industrial landforms are located in this area. Administratively, this area extends into

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the municipalities of Slovinky, Krompachy, Poráč, Rudňany, Závadka and Markušovce located in the northwestern part of the Košice region. Geologically, the area is located at the interface of three geological units of the Gemericum: the Gelnica and Rakovec sequences and the Spiš Nappe. From a geomorphological point of view, the studied area belongs to the geomorphological units Hornádska kotlina and Volovské vrchy and the subunits Hornádske podolie and Hnilecké vrchy. Mining, which resulted in the formation of the studied anthropogenic relief forms, is closely related to the mineral wealth of the area. Iron and copper ores were mainly found here. Various convex and concave anthropogenic relief forms can be identified here. In this article, we will focus only on the largest of them in terms of area. In addition to them, numerous tunnels, shafts, heaps, and pings can be found in the region, which complete the picture of the anthropogenic influence on the landscape of Central Spiš. Anthropogenic geomorphology and the classification of forms have been addressed by several authors, such as Harvey [1], Goudie and Viles [2], Tarolli et al. [3], Mossa and James [4], Schaetzl and Marston [5], who have classified and defined individual forms of anthropogenic relief. Research into anthropogenic landforms is also directly related to their impact on the surrounding environment. These impacts include accelerated surface weathering, changes in hydrological and hydrogeological conditions, disruption of the stability of the rock system, and changes in the circulation of water between the surface and the subsoil. The deposited tailings represent the entry of highly reactive minerals onto the surface [6]. It should be noted that the emergence of anthropogenic landforms can also have a positive impact on the landscape, e.g., by creating opportunities for the development of some forms of geotourism or by initiating the emergence of new plant and animal communities that are sensitive to landscape fragmentation [7]. The means of restoring the landscape to a state as close as possible to its original structure is reclamation. There are various methods for landscape reclamation, but the approach taken always depends on the extent of the damage and the specific characteristics of the site.

Mining and processing of ores, especially iron, copper, and silver ores and other polymetallic ores, has a long history in the Spiš region. The investigated tailings ponds, mine collapse, and quarry are the results of increased production in the 19th and 20th centuries. The village of Slovinky was founded as a mining settlement, with the first written mention in 1368. The territory of Slovinky and the adjacent town of Gelnica represented significant reserves of ore wealth in the form of several ore veins. Iron from Slovinky mines had a low copper content, so electromagnetic ore separation was used here as early as 1909 [8]. In the 1960s, the accident at the Slovinky tailings pond led to the creation of a new tailings pond in the cadastral area of the town of Krompachy. Since the 1980s, mining has been reduced in the entire region. In October 1991, the Ministry of Economy decided to liquidate the mines and processing plants, and in 1993 the last cartload of copper ore was removed from the Slovinky mine. Likewise, copper, silver, and gold ores were mined in Rudňany and Poráč during the 18th and 19th centuries. A document from 1332 mentions the existence of copper in the village of Poráč, and contemporary records show that King Bela IV invited colonists with experience in ore mining there. At the end of the 19th century, the development of iron ore and mercury mining began in the region. During the existence of Czechoslovakia, the Rudňany Iron Ore Mine (located in a village between Poráč and

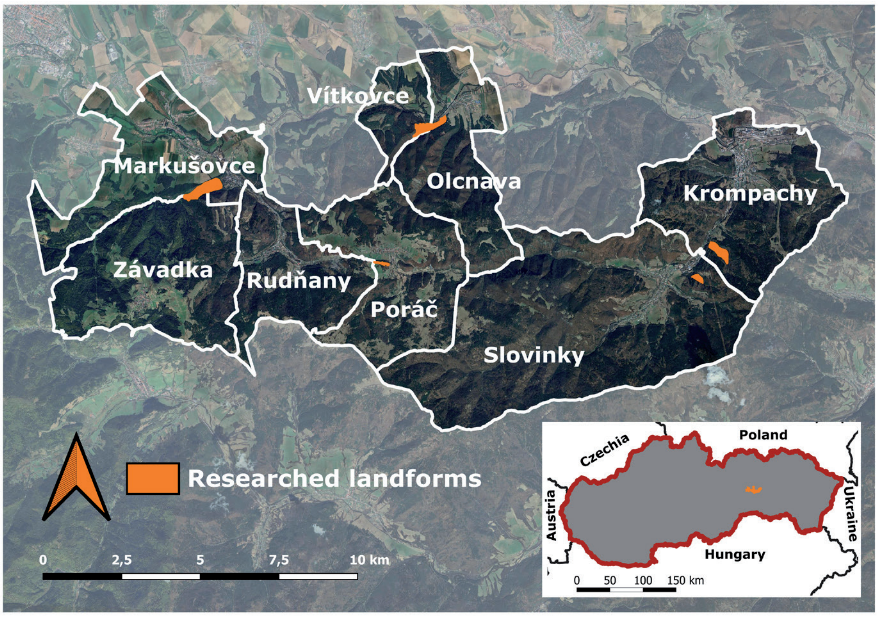

Fig. 1. Location of the studied landforms.

Markušovce) was the largest iron ore mining enterprise. The reserves of siderite, chalcopyrite, and tetrahedrite with mercury, silver and antimony admixtures gradually ran out. After 1989, mining became unprofitable, and only barite mining remained in the Poráč mine. The existence of the tailings pond in Markušovce is linked to the plant in the village of Rudňany. The mines experienced a boom in production during the 20th century; the companies belonged to German concerns during World War II. After 1945, the plants were part of the national enterprise Železorudné bane Spišská Nová Ves. In the 1960s, there was a boom in development; the state invested in the construction of a mining and processing complex in the village of Markušovce. After 1992, these mines were also closed and liquidated as part of the decline in mining [9]. The village of Olcnava has been a source of building material for a considerable time. The first decision on the permit for mining was issued in 1987.

As a result of the cessation of most mining operations in the Slovak Republic, unwanted legacies in the form of various anthropogenic landforms remained in the country. A special category comprises tailings ponds, the contents of which are usually hazardous. These landforms are often abandoned and lack designated owners responsible for their maintenance. Many mining and ore processing enterprises have turned into large brownfields in recent decades. The Spiš region is no exception. It is in this respect that our research is novel. It presents a set of data on the nature of environmental loads, basic information on the content of hazardous elements, and a proposal for initial measures to prevent the spread of pollutants into the surrounding landscape. Our research represents a comprehensive package of information necessary for further decision-making and effective management of the landscape with the aim of long-term sustainability of a high-quality environment.

The issue of anthropogenic geomorphology in our area of interest has already been addressed by Čech [10]. This work was devoted to the possible use of old mining sites as places suitable for geotourism. Krokusová [11] focused her work on the Halňa tailings pond in the town of Krompachy and the possibilities of its reclamation. The reclamation of this site has since been successfully completed. Hronček [12] deals with the possibilities of new use of old mining areas for the purposes of mining tourism. Similarly, anthropogenic relief forms in other locations in Slovakia were addressed by Michaeli et al. [13, 14], Michaeli and Boltižiar [15], Hronček et al. [12], or Pavolová et al. [16].

The main objective of the article is to obtain information on the impact of the studied anthropogenic relief forms on the landscape. We achieved this by obtaining 3D models that allow the precise identification and measurement of anthropogenic forms in the field. The models were created using the "Structure from Motion" method as a relatively inexpensive and accessible alternative to ground-based laser measurement. We also obtained an overview of the content of the stored material and assessed the degree of environmental threat posed by the studied relief forms. Last but not least, we proposed measures to improve the quality of life of the population and the quality of the landscape.

Materials and Methods

The studied area is located at the interface of the geomorphological units of the Hornád Basin and the Volovské Hills. It represents an area with a significant concentration of anthropogenic relief forms. Based on the reconnaissance survey, we selected some of them and created detailed images and 3D relief models, which we compiled using the photogrammetric method Structure from Motion (SfM). In our work, we used an autonomous drone with a camera and a series of precisely targeted points on the earth's surface using a Topcon RTK GNSS HIPER HR device with a Topcon FC-5000 field computer, which has high targeting accuracy with a horizontal deviation of 5 mm and a maximum vertical deviation of 10 mm and is also resistant to water and dust, as required by the conditions in the surveyed area. During targeting, we had GPS, GLONASS, Galileo, and BeiDou satellites available, and this accuracy was subsequently transferred to the accuracy of the obtained models. The drone used for image acquisition was a DJI Phantom 4 PRO quadcopter with an ultra HD camera, a three-axis stabilized gimbal, a positioning system, and anti-collision sensors. The camera is capable of rotating independently and taking sequential shots. The drone is equipped with a Flight Autonomy system with image and infrared sensors and can perceive the surroundings in five directions and avoid obstacles. The limiting factor in flight is battery life, which places additional requirements on favorable weather conditions to allow for its maximum possible flight time. Following the field acquisition of the raw data described above, the inputs were processed using Agisoft Metashape software into the form of a so-called point cloud. This first graphic output needs to be transformed from the WGS 84 system used by the drone to the system used in Slovakia, S-JTSK/Krovak East North. A powerful workstation is important for processing the dense point cloud, from which a digital relief model and an orthorectified surface image are subsequently created. The resolution is very high, 2 cm per pixel. The advantages and use of relief models in geography have been discussed by several authors, e.g., Gallay [17] and Leitmannová and Gálová [18]. The SfM method itself and the comparison of its outputs with those of airborne LiDAR have been discussed by Crosby [19].

For the purpose of determining the composition of the studied relief forms, we took samples of material from the tailings ponds and the mine collapse and subsequently analyzed them in the Geoanalytical Laboratories. Heavy metal concentrations in samples from the tailings ponds were determined using X-ray fluorescence spectrometry and atomic absorption spectrometry using a mercury analyzer; pH was determined using electrochemistry. When determining the composition of the fly ash from the collapse, the laboratory used X-ray fluorescence spectrometry, inductively coupled plasma atomic emission spectrometry, inductively coupled plasma mass spectrometry, and gamma-spectrometric determination with an HPGe detector for radioactive elements. The sludge samples represent homogeneous material originating from a single factory. The sludge was sampled at a depth of 50 cm to avoid surface horizons depleted by wind and water. The sinkhole sample also represents a homogeneous mixture of fly ash for which the sampling depth is irrelevant. The number of samples is not large, but it is sufficient for our purpose of determining which hazardous substances are present in high concentrations at these locations.

Results and Discussion

The research was focused on larger-area tailings ponds, a mine collapse, and a quarry, which represent a selection of the total number of anthropogenic landforms (Fig. 2, Table 1).

Markušovce Tailings Pond

It is situated on the border of the cadastral territories of the municipalities of Markušovce and Závadka, and its shape follows the valley of the Markušovský stream. Nearby is the Želba plant in Rudňany, from which the flotation sludge stored here comes. Including the dam, it is 1.3 km long and between 160 and 340 m wide. The thickness of the deposited material is uneven, and the estimated current volume is 9,901,160 t (Fig. 3). According to Slovak law, specifically 514/2008 Coll. on waste management from the mining industry, it is classified as category A. It represents a closed storage facility with subsequent material utilization [20]. From the south and the north, it is surrounded by forested slopes for half of its length. On the western side, it is separated by a dam from the continuing Markušovská Valley. The stream is led under the tailings pond and is allegedly isolated from the tailings pond. On the northeastern side, the tailings pond is separated by an embankment and a narrow strip of vegetation, beyond which lies agricultural land. On the eastern side, there is a main dam in the direction of the processing plant. The tailings pond area is not flat; it slopes slightly from the east and west sides to the central part. There, the water level varies throughout the year and is supplied by water flowing in from the surrounding slopes. Vegetation occurs in several places here, especially where water is concentrated. Another element of concern is the occurrence of municipal waste in the southwestern part, where the sludge pond area is most easily accessible by car. In the eastern part

Table 1. Size of chosen landforms.

Location	Area (ha)
Markušovce tailings pond	39.1
Olcnava quarry	20.1
Kaligrund tailings pond	17
Bodnárec tailings pond	3.5
Poráč mine collapse	2.8

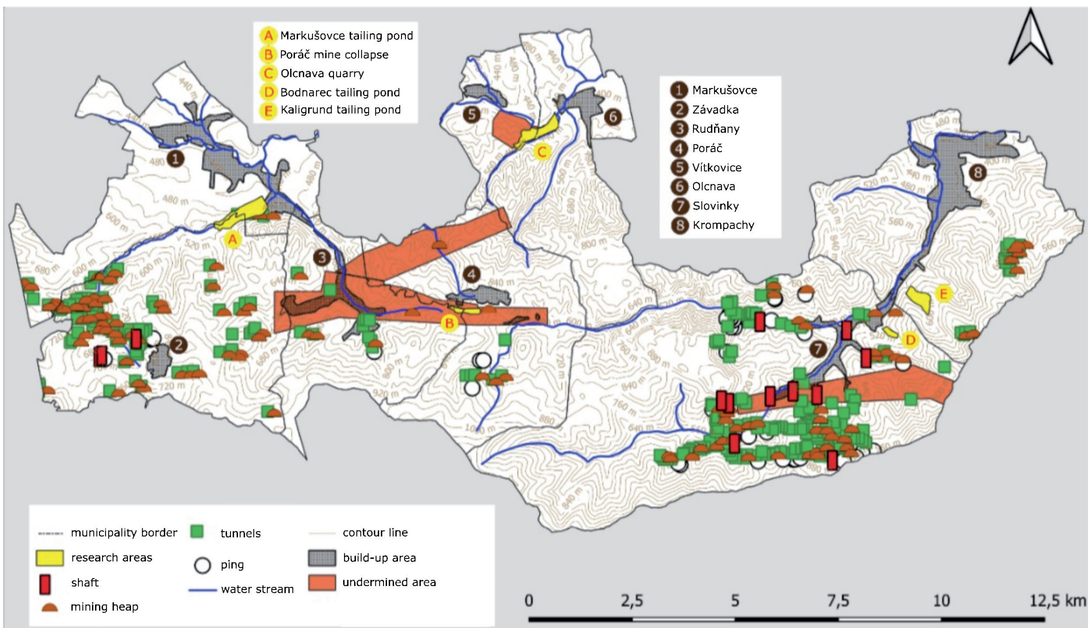

Fig. 2. Anthropogenic impact on the landscape in the region through mining.

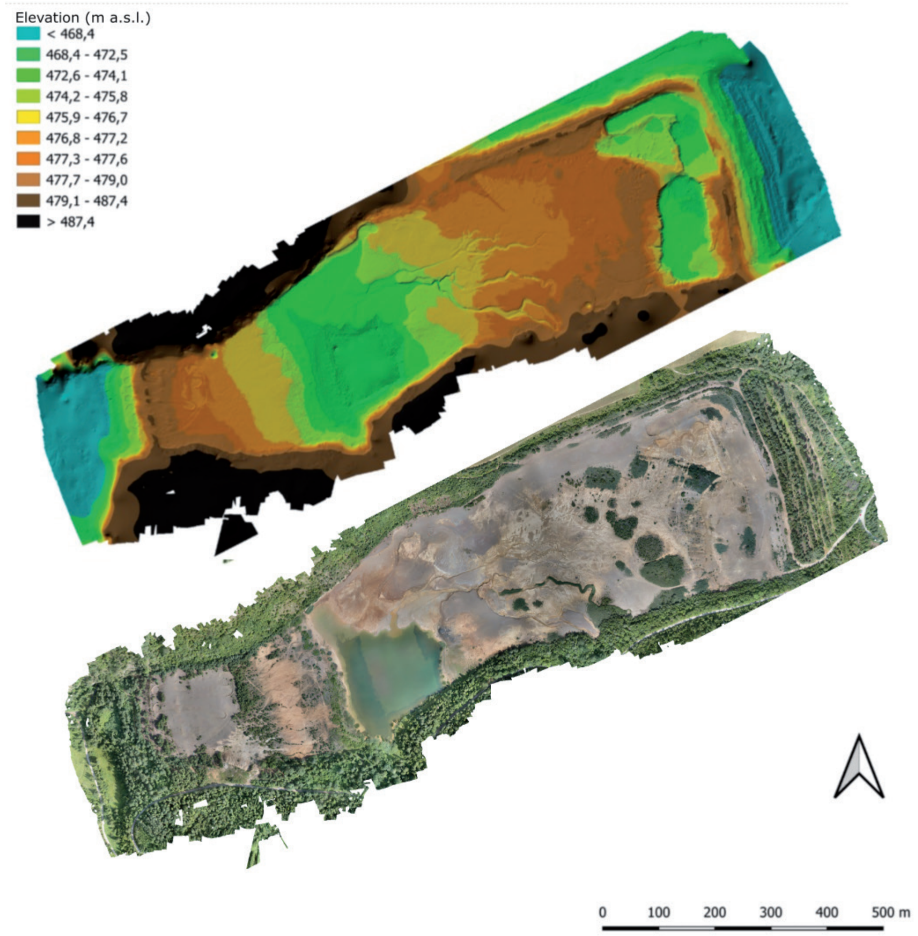

Fig. 3. Elevation ratios and orthophoto of the Markušovce tailings pond.

of the tailings pond, the original structure has been disturbed by dredging for the purpose of extracting barite. The barite content was apparently insufficient for the continuation of this activity, which is a pity, since secondary use of this material would be the best way to get rid of this industrial waste in the country. After the end of the use of this tailings pond, natural processes began to prevail again, as evidenced by linear water-flow features that gradually transform the man-made relief form. The aforementioned mining site was also obliterated by water and wind activity. We cannot forget the secondary human activity in the form of tire tracks, which indicates that this area is popular with motorbike and quad bike riders, although their presence in the sludge pit is, of course, illegal. Given the results of the samples taken, it is absurd that local residents are exposed to swirling, health-damaging dust from flotation sludge in this way, not to mention the health of the riders themselves.

Poráč Mine Collapse

The mine collapse is above the Droždiak vein in the cadastral area of the municipality of Poráč. Between 1969 and 2007, there was a vertical movement of 7.983 m, of which almost 5 m occurred between 1997 and 2007. Since then, the area has been filled with power plant fly ash from the Košice heating plant and the Bukocel Vranov power plant and with furnace slag from the Prakovce plant [21]. The collapse was caused by barite mining, during which the material previously left as backfill in the area after siderite mining was removed. The creation of this anthropogenic form of relief even resulted in the relocation of the road to the municipality of Poráč twice. Even during our survey, the cave-in was being filled in, so our model captures one phase of its development. The mine cave-in runs in a west–east direction and is 600 m long and 55 to 120 m wide (Fig. 4). The northern part is lined with bushes and trees that separate the collapse from fields and residential houses, while the distance to the residential area is only 210 m. East of the collapse is the current road to the village of Poráč. The western and southern parts are lined with meadows and strips of trees and bushes. The full depth of the collapse cannot be seen today because it has been filled in. The deepest sunken depression is in the central part of the collapse. What surprised us was the huge amount of municipal waste that residents dispose of illegally by dumping it into the collapse. Of course, no official document concerning the rehabilitation of the collapse zone mentions the use of municipal waste to fill it.

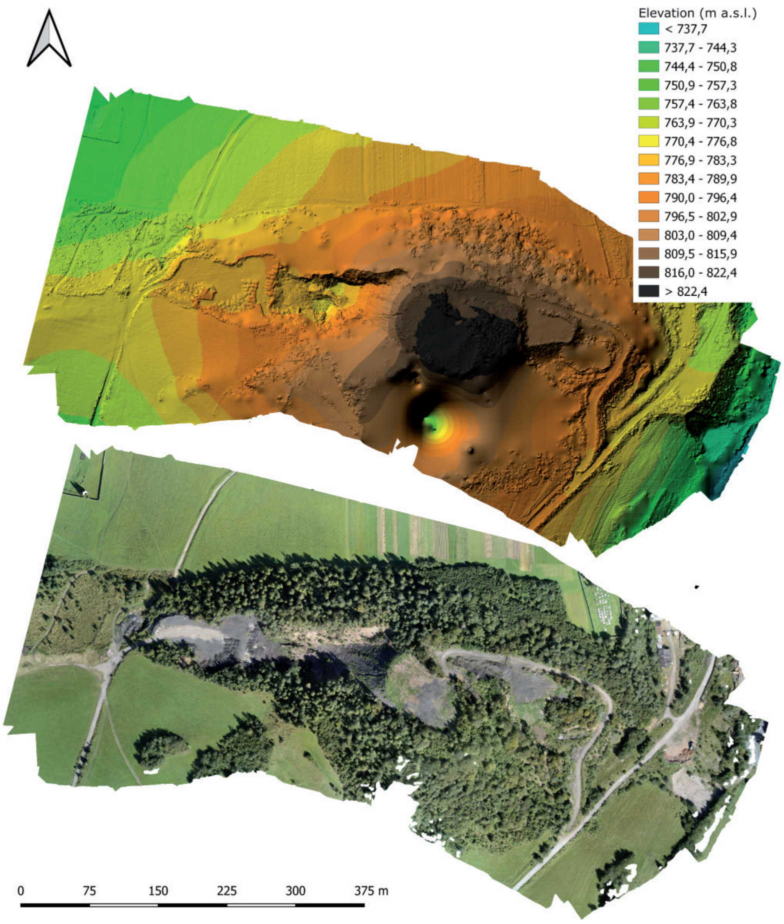

Fig. 4. Elevation ratios and orthophoto of the Poráč mine collapse.

Bodnárec Tailings Pond

It is located in the cadastral area of the municipality of Slovinky and has not been actively used since 1968. Today, a dog park can be found in part of it, and the rest is still identifiable in the terrain, although the edges of the area are gradually being encroached upon by the surrounding forest. Over the past 57 years, its area has still not been fully covered with grass or other vegetation. A stream flows around it along the northern and eastern sides in an artificial channel, with its red color indicating that the waters are inappropriately mineralized. The other sides of the old tailings pond are lined with trees and shrubs. The tailings pond dam is difficult to distinguish in the terrain (Fig. 5).

Kaligrund Tailings Pond

It is located on a slope above the village of Slovinky, but within the cadastral territory of the town of Krompachy (Fig. 6). It is a valley tailings dam for ore production sludge. It is currently unused, and slag from the Kovohuty Krompachy enterprise can be seen on the surface. It is built in difficult terrain, and most of the stored waste was transported from the Slovinky mine using three pumping stations. Until 1993, when these mines were closed, flotation sludge was stored there; later, only the above-mentioned slag was stored. Since the tailings dam is classified as a water structure, its dam is the highest water dam in Slovakia. There is almost no vegetation on this tailings dam; in the southeastern part, concrete panels and a metal pipe served as a material supply point. The dam has concrete channels for rainwater drainage and also sensors, which are regularly destroyed by local Roma communities. The tailings dam with its 113-m-high dam poses a danger if its condition is not monitored.

Olcnava Quarry

Among the listed anthropogenic forms in the studied area, the quarry is the only active one, i.e., actively used. The materials extracted are limestone, dolomitic limestone, dolomite, marl, and breccia of the Middle and Upper Triassic. The reserves have been exploited since 1965. The mining method involves the separation of rock using large-scale blasting. Water from the Hornád River is used in mining and processing. A significant part of the entire surveyed area is used as a landfill for various sizes of mined material. The mined part is a multi-level quarry with five benches. Due to the daily work, vegetation in the quarry is almost nonexistent (Fig. 7).

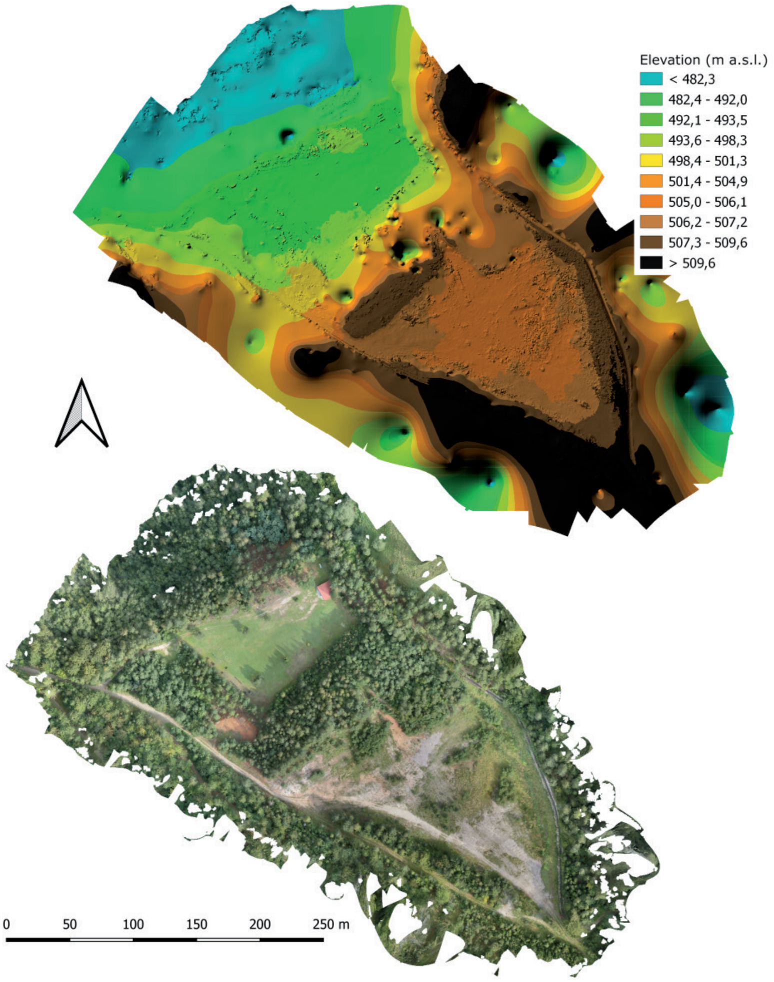

Fig. 5. Elevation ratios and orthophoto of the Bodnárec tailings pond.

Analysis of Hazardous Substances

Due to the potentially hazardous substances present in the studied landforms, we took samples to determine the exact composition. Laboratory analyses show that the collapse zone filled with fly ash has a significant arsenic content of 490 mg/kg (Table 2). Since fly ash often contains radioactive elements, we also had the samples analyzed for the presence of radioactive potassium, thorium, and radon, but the measured values did not exceed the permitted limits. However, we believe that it is necessary to consider the contamination of mine waters and other groundwater with fly ash. The three presented tailings ponds in the studied area contain material originating from the processing of copper and iron ores, although in the case of the Kaligrund tailings pond, slag from the Krompachy metallurgical works was deposited in its upper part. The results from the Markušovce site clearly show copper as the dominant element at all sampling points; after all, it is waste from a copper ore processing plant. In the unmined western area, mercury is in second place with a high content of 505 mg/kg. We also recorded the highest barite content at the Markušovce tailings pond. The highest value in the unmined areas reaches 223,500 mg/kg. The Bodnárec tailings pond showed the highest barite content among the elements searched for,

Table 2. Sampling results from research locations (mg/kg).

Location	Mo	Be	B	As	Cu	Hg	Sb	Pb	Barite
Poráč	4	16	234	490	x	x	x	x	x
Markušovce	x	x	x	150	1183	505	251	x	223500
Bodnárec	x	x	x	858	409	5	24	x	1044
Kaligrund	x	x	x	683	1	6244	9982	3050	8811

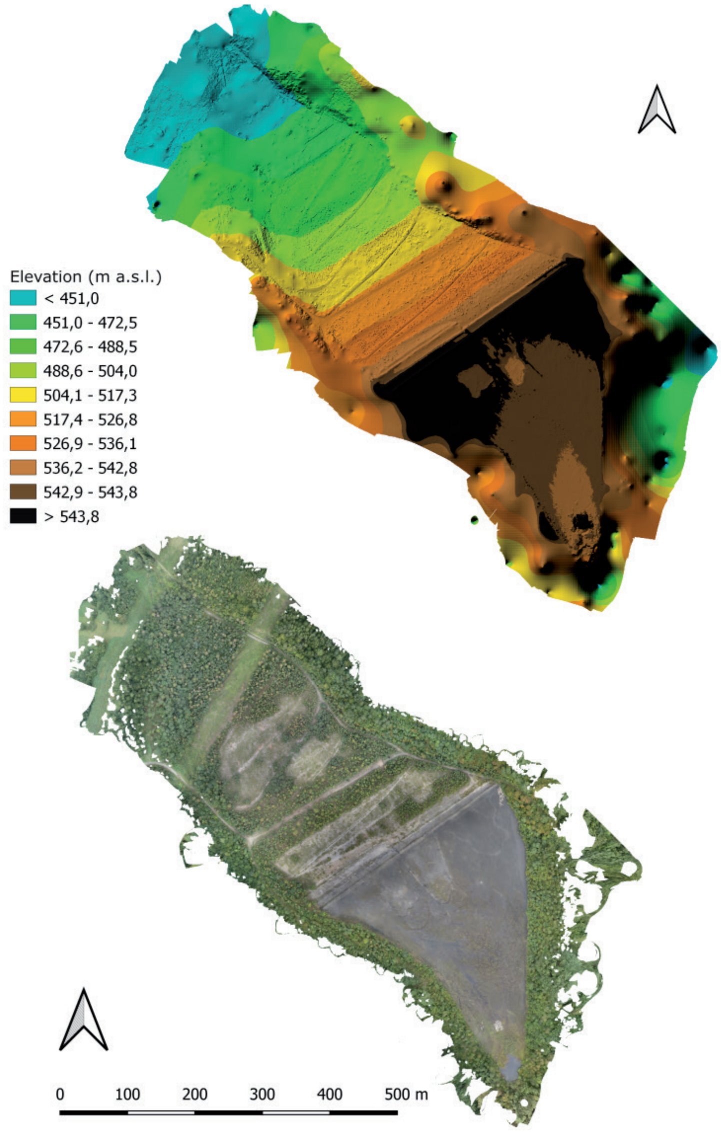

Fig. 6. Elevation ratios and orthophoto of the Kaligrund tailings pond.

but it was significantly lower than that at Markušovce. Of the heavy metals, arsenic had the highest concentration - 858 mg/kg, followed by copper and other elements with negligible values. We also looked for lead in the samples from both Markušovce and Bodnárec, but the result was less than 5 mg/kg. At the Kaligrund tailings pond, the situation is different in the resulting samples. Antimony had the highest concentration here with a value of 9982 mg/kg. Mercury, lead, and arsenic had high values.

The negative impact of heavy metals on soil and vegetation is well known from many works, e.g., Nyiramighisha et al. [22], Alsherif et al. [23], or Kacholi and Sahu [24]. Knowledge of the content of heavy metals in the investigated anthropogenic landforms opens up further possibilities for studying the impacts on the surrounding landscape in detailed future research focused on the content of these elements in water and soil.

The values indicating the heavy metal content in the samples taken from all three tailings ponds are too high, making it unsafe to allow wind erosion of the surface material or the dispersal of heavy-metal-containing material onto agricultural land, forest communities, and settlement areas in the studied region. Based on the information we have found, we have excluded the Olcnava quarry area as a problematic element, as it is in proper operation and the extracted material does not pose any risks. The area of the mining collapse in the village of Poráč is already in the active phase of rehabilitation. The remaining three tailings ponds are located near residential areas or actively used agricultural land. We assessed each site individually according to its specifics. The oldest investigated object is the Bodnárec tailings pond, part of which is now reclaimed. We recommend covering the remaining area to prevent material deflation. It is also necessary to pay attention to the watercourse flowing nearby to prevent it from polluting the Slovinky stream into which it flows. According to reports, the Markušovce tailings pond is regularly inspected. It was originally designed for

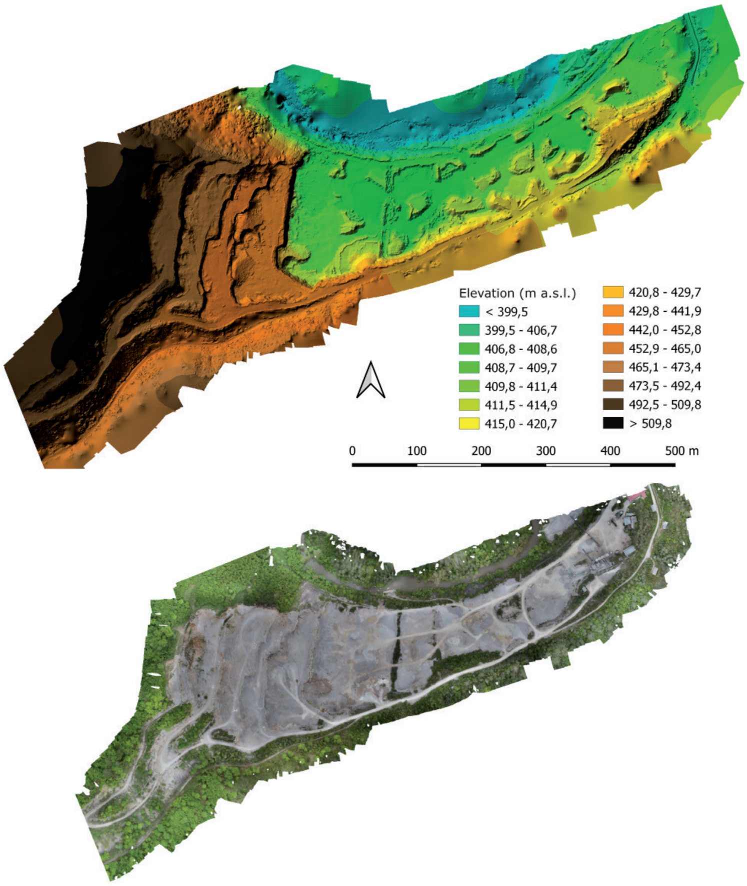

Fig. 7. Elevation ratios and orthophoto of the Olcnava quarry.

a higher volume of material than is currently deposited in it. The tailings pond does not pose a risk of dam failure or damage from torrential rains. Wind erosion is a bigger problem, as fine material can be carried by the wind onto adjacent agricultural land on dry days. The Kaligrund tailings pond is the most hazardous of the investigated sites. It can be a threat to the population and the environment. The dam structure may be at risk from landslides; drainage waters contain some heavy metals. High values of antimony and arsenic are also confirmed by our own measurements. Concerns about the safety of the dam are certainly also raised by storms with heavy rainfall in recent years, which were not common in our area. The area where the material has been deposited lacks any form of wind protection. At all three tailings ponds, at least protection against wind erosion is required in the form of the usual system comprising an impermeable layer followed by inert soil with the possibility of vegetation growth to strengthen it (Fig. 8).

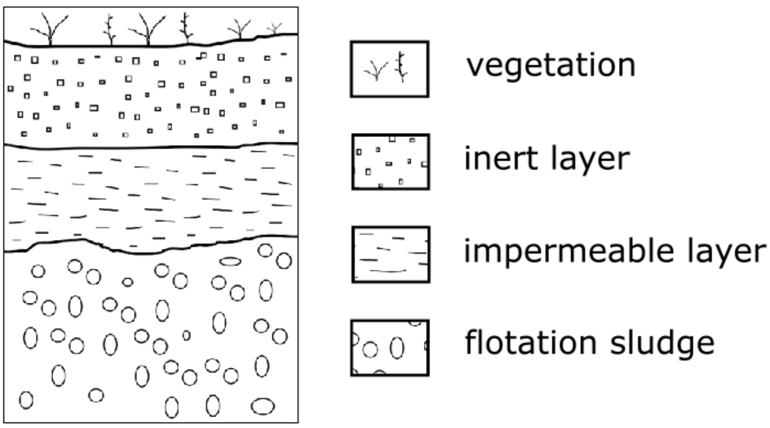

Fig. 8. Insulation from the elements.

Reclamation would prevent not only wind erosion but also seepage of rainwater carrying heavy metals. Biological reclamation in the form of topsoil and grass planting would, in addition to the aforementioned benefits, integrate these large, disturbing areas back into the cultural landscape. It is appropriate to strive, if not for complete reclamation, then at least for the isolation of the deposited sludge so that it is separated from the surrounding environment. In the future, with new technologies, private investors could use what we today call mining or industrial waste as a deposit of secondary raw materials. Studies that dealt with the restoration of vegetation in stressed areas include those by Prausová et al. [25], Wang et al. [26], Feketová et al. [27], or Yibin [28]. These studies were conducted in conditions similar to those in polluted areas and demonstrated the restoration of both soil processes and vegetation cover.

Conclusions

The potential for vegetation restoration varies. The quarry in Olcnava is still active, but after extraction ceases there will be no problem with secondary use, as the extracted material is neither harmful nor dangerous. From the perspective of landscape cover, the mine sinkhole is in the middle of woodland, and after the application of the insulating layer, which we propose in the discussion, we assume a relatively simple restoration of vegetation cover. Of the remaining sludge ponds, the oldest one in the municipality of Slovinky has already been partially reclaimed and should be the easiest to integrate into the landscape after sufficient isolation. The Markušovce tailings pond with a significant exposed area of stored material has the potential to expand natural areas due to the proximity of forests, once sufficient conditions are created. The Kaligrund tailings pond presents the most significant challenge in efforts to restore the natural landscape and prevent the transfer of materials due to wind erosion. Given the high dam, this site would require more in-depth research involving an expert who would assess the suitability of specific vegetation types in relation to the potential threat to the dam structure. The diversity of the presented sites shows the need to further address these environmental pressures, especially given their significant differences.

The most important results of our work are high-resolution relief models, identification of major pollutants, and a proposal for landscape remediation. We have at our disposal high-quality and detailed models of problematic environmental burdens. Thanks to them, we have their dimensions, dam height, slope, altitude, etc. Associated orthophotos also allow an overview of the surrounding vegetation and the character of the landscape in which the loads are situated. The use of these models represents the possibility of modeling wind or water erosion. They are also suitable for analyzing already ongoing secondary modification of these forms by natural forces. The photogrammetric method used has its advantages and limitations. LiDAR scanning is more advantageous if there is vegetation in the area, but it is also more financially demanding. In addition to a detailed relief model, the photographic method also allows for obtaining a detailed orthorectified image. Its use is advantageous in cases where the surveyed area is not covered by large areas of dense vegetation, access is not blocked by, for example, high-voltage electric poles, or there are no nesting protected bird species in the area that would perceive the drone as a threat and would be threatened by contact during imaging. Its accuracy is also strongly dependent on the quality of georeferencing. The use of ground control points is essential to eliminate systematic errors, such as the "doming effect" in linear imaging.

We would like to develop further studies on this basis regarding specific locations, their specific characteristics, and the appropriate approach to each location. The obtained results of sampling give us an overview of the more serious pollutants, which we can then focus on in further research to find them in the landscape as evidence of contamination. Thanks to the results of the sample analysis, we have measurable evidence of the high risk posed by these facilities. We believe that their existence without further plans to stop the transfer of pollutants is outrageous. The proposed measures represent the minimum possible isolation of pollutants from the landscape, but the information obtained represents a basis for further research not only in the studied area. The same problem with residues from ore processing also occurs in other regions of our country. The results obtained are invaluable for state and local governments in planning the restoration of the devastated region, particularly concerning sustainability and environmental health.

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AI Usage Disclosure Statement

There was no AI used.

Conflict of Interest

The authors declare no conflict of interest.

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