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Original Research Article

MONITORING AND ANALYSIS OF GROUND MOVEMENTS IN THE BABINA POST-MINING AREA

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A b s t r a c t

Ground deformations in post-mining areas, such as subsidence and uplift, can occur for many decades after the end of mining. This article presents the findings of a5-year monitoring and analysis of ground movement in the post-mining area of the "Babina" mine, situated within the glacitectonic Muskau Arch. The study was aimed at analyzing continuous ground deformations observed using precision levelling. The measurement data were statistically processed and visualized using maps and graphs. The results indicate significant ground movements that vary seasonally and between different parts of the complex post-mining area. This points to additional research questions on the causes of these movements that could be attributed to groundwater table variation that should be further analysed. The article draws attention to the need of continuous monitoring of post-mining sites and integration of measurement results with additional data to gain a more comprehensive understanding of the processes taking place in post-mining areas.

Keywords: precision levelling, descriptive statistics, lignite, glaciotectonic area, GIS

1. INTRODUCTION

Post-mining areas often experience secondary ground movements, both continuous and discontinuous. These deformations can occur even decades after the end of mining [1-5]. Continuous deformations, such as subsidence, occupy large areas without breaking the continuity of the rock layers, which makes them more difficult to observe, especially in the case of small movements [6]. They are the result of changes in the rock mass structure caused by mining operations, involving subsidence, horizontal movement and ground surface deformation [7-8]. Discontinuous deformations, such as sinkholes and cracks are usually the result of the sudden collapse of post-mining voids, especially the shallow ones.

The cessation of mining also results in the gradual restoration of groundwater levels, which can have a significant impact on land deformation and land cover. Changes in groundwater levels, exert pressure on rock structures, leading usually to uplift of the land [9]. In studies conducted in the Chinese

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Lowlands, it was observed that depletion of groundwater resources led to vertical movements of the ground surface, which was confirmed using Global Navigation Satellite System (GNSS) and satellite data from the GRACE mission, showing a correlation between water level fluctuations and land movement [10]. Similar phenomena have been observed in Poland - after the closure of anhydrite and copper mines, groundwater changes caused land uplift. Through the use of methods such as PSInSAR and traditional surveying techniques, accurate analyses of land movements have been carried out, indicating an increase in elevation of up to 29 mm per year [11]. Other studies have also shown that depletion of groundwater resources can lead to vertical movements of the land surface, as confirmed by GNSS and satellite data [12-15].

These examples show that during groundwater level recovery, hydrostatic pressure change in post-mining areas can lead to subsidence and uplift of post-mining areas. This process can lead to deformations destroying shallow underground workings and damaging infrastructure on the ground surface. For this reason, monitoring post-mining sites both during the rise in ground water levels and after they have stabilised is important to protect infrastructure and for general safety. Such measures identify areas vulnerable to further movement and enable the management of risks associated with ground deformation in post-mining regions [16-18].

Various surveying techniques such as levelling, GNSS, satellite radar interferometry (InSAR) and 3D laser scanning are used to monitor ground movements [4, 19-20]. Precision levelling provides the highest accuracy measurements, which is crucial for monitoring small ground movements in post-mining areas, although it is a time-consuming and yields information limited to the controlled benchmarks [21-23]. Techniques based on GNSS allow precise monitoring of ground movement in real time and can detect vertical and horizontal deformations with millimetre accuracy. This is useful in post-mining areas but again costly and limited in space [24-26]. Alternatively, InSAR is an efficient technique for continuously mapping surface deformations with high frequency over large geographical regions, enabling the identification of hazardous areas. However, its use is limited in densely vegetated areas and presence of surface water. In studies conducted in the Upper Silesian Coal Basin, satellite radar interferometry technique was employed for the purpose of monitoring ground movements in mining area. The results demonstrated that the InSAR method enables the acquisition of a spatial image of subsidence troughs occurring above the area of underground mining exploitation, over a vast geographical region. This, in turn, allows for the delineation of current hazard regions [27]. The technology was applied to monitor post-mining ground deformations in various countries [1, 4, 28-29] including Poland, where Persistent Scatterer Interferometry was employed for example to monitor sinkhole occurrence over shallow abandoned coal mines [30]. InSAR and LiDAR have also been used to map surface deformation across entire mining regions [13].

In addition, the integration of survey data in geographic information systems (GIS) has proven to be highly effective in analysing and visualising ground deformation. These GIS-based techniques enable the identification of areas at risk and facilitate decision-making processes for land use planning and infrastructure development [31-32].

It should be mentioned that geophysical techniques such as Ground Penetrating Radar (GPR) are used in the monitoring and analysis of post-mining areas [33-35]. GPR operation is based on the emission of electromagnetic waves in the microwave range that penetrate deep into the ground and reflect off different geological layers, cavities or other subsurface anomalies. The reflected signals are then recorded and analysed, allowing the detection and mapping of subsurface features that may indicate potential risk of ground instability or subsidence [36-37].

The integration of ground-penetrating radar with other surveying techniques, such as GNSS and 3D laser scanning, has proven to be highly effective in providing a comprehensive understanding of ground movement in post-mining regions. For example, the combination of GNSS data for precise positioning and GPR data for subsurface visualisation can enable the accurate delineation of areas at risk of ground deformation [34].

It should be noted that post-mining areas rarely are covered by systematic monitoring and information on the extent of former mining often disappears over time.

Our study, connected with the National Science Centre financed projects that involve comprehensive monitoring of the post-mining environment, focuses on assessing the presence of continuous ground movements in the area of the "Babina" lignite mine that operated until the mid-1970s of the 20th century. The aim is to statistically analyse, based on the results of repeated levelling measurements in a control network set-up for this purpose, if ground movements are present 5 decades after the end of mining activity.

2. STUDY AREA

The area of the lignite mine "Przyjaźń Narodów - Babina Shaft" (short name "Babina"), is located in the western part of Poland, close to the border with Germany. It was the last operating mine in this part of the country. The area is characterised by a relief with heights not exceeding 200 m above sea level and a slight slope, except in places such as heap embankments or former open-cast pits (Fig. 1).

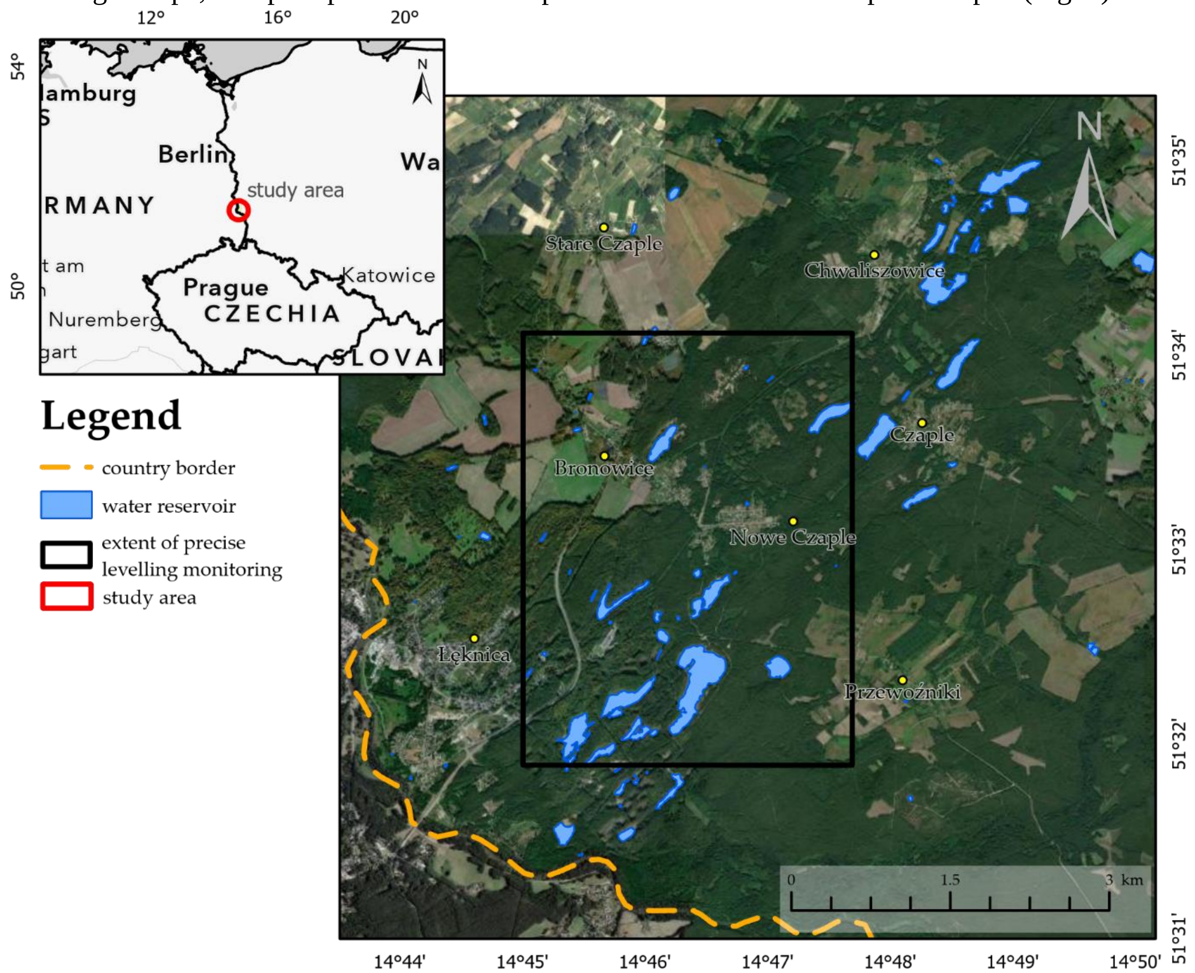

Fig. 1. Location of the study area

Geomorphologically, the study area is part of the Muskau Arch, a transboundary glacitectonic structure, that probably formed during the South-Polish glaciation and was remodelled during successive glacial periods. Parallel hills, weathering ditches, elongated valley depressions and the valley of the Nysa Łużycka River, which crosses the Muskau Arch, are characteristic in the picture of the region [38-39]. Geologically, the area belongs to the Pre-Sudetic monocline, consisting of Precambrian crystalline rocks, foliated Caledonian-Hertzian Palaeozoic formations and the Zechstein-Mesozoic-Cenozoic platform cover. Within the Muskau Arch there are rich mineral deposits, including lignite, whose exploitation at the "Babina" mine lasted from 1921 to 1973 [40-41].

Mining of shallow and inclined lignite deposits (up to approx. 100 m below ground level) was carried out with both the underground and open-pit methods. The latter one dominated in the last phases of the mine operation. Exploitation of other resources such as clays was done with open-pits.

The closure of the "Babina" mine was due to unfavourable geological and mining conditions, which significantly affected its profitability. Following the closure of the mine, the area was rehabilitated. Numerous open pits were transformed into water reservoirs, some were filled with waste rock. Currently, the post-mining area is characterised by a picturesque landscape dominated by colourful lakes that formed in places of former mining open-pits (Fig. 2), outcrops of lignite, waste heaps with some devoid of vegetation due to unsuccessful reclamation processes, forests dating back to times before mining activity and those planted during reclamation works. The study area now constitutes part of the transboundary UNESCO Global Geopark Muskau Arch. It was established in 2015 in recognition of due to its unique geological and post-mining landscape features [39, 42-43]. The geopark is a popular destination for tourists offering hiking trails, viewpoints and educational panels describing its geological and historical significance [44].

Fig. 2. Photos of the study area taken from a drone (Becker M., 2024)

3. METHODOLOGY

The approach adopted for monitoring, the potential, present-day ground movements in the post-mining area of interest (AOI) included setting-up of a control levelling network designed to cover the entire area subjected to underground and open-pit mining and perform repeated, annual, measurement campaigns. Details of the construction of the network and the levelling campaigns are given below.

3.1. Measurement network

The constructed survey network consists of 99 controlled benchmarks stabilised in concrete poles, of which 26 benchmarks are located in the main levelling lines and 73 are controlled benchmarks forming so-called grids. The controlled points were stabilised in PVC-covered concrete poles at a depth of up to

1 meter below ground level, exceeding the freezing depth of 0.8 meters as specified by Polish standard PN-B/03020 [45]. This installation depth provides additional protection against the impact of freezing and thawing cycles, thereby ensuring greater stability. A sketch of the designed stabilisation of controlled points and the stabilisation process is shown in Figure 3.

Fig. 3. Design and construction of controlled points

The main layout of the grid is formed by levelling lines, connecting the controlled points. The measurement network consists of 39 levelling sections, which enable determination of vertical movements across the entire grid (Fig. 4.).

Four higher grade benchmarks from the national levelling network and located beyond the boundaries of the post-mining area were included as reference points. These national network benchmarks are labelled: 302, 403, 407 and Bolec2 in Fig. 4. Their stability was verified during each measurement campaign. These measurements have been carried out over a continuous period of at least 24 hours. The coordinates obtained from these sessions were systematically compared to each other, and the absence of significant discrepancies confirmed the stability of these points.

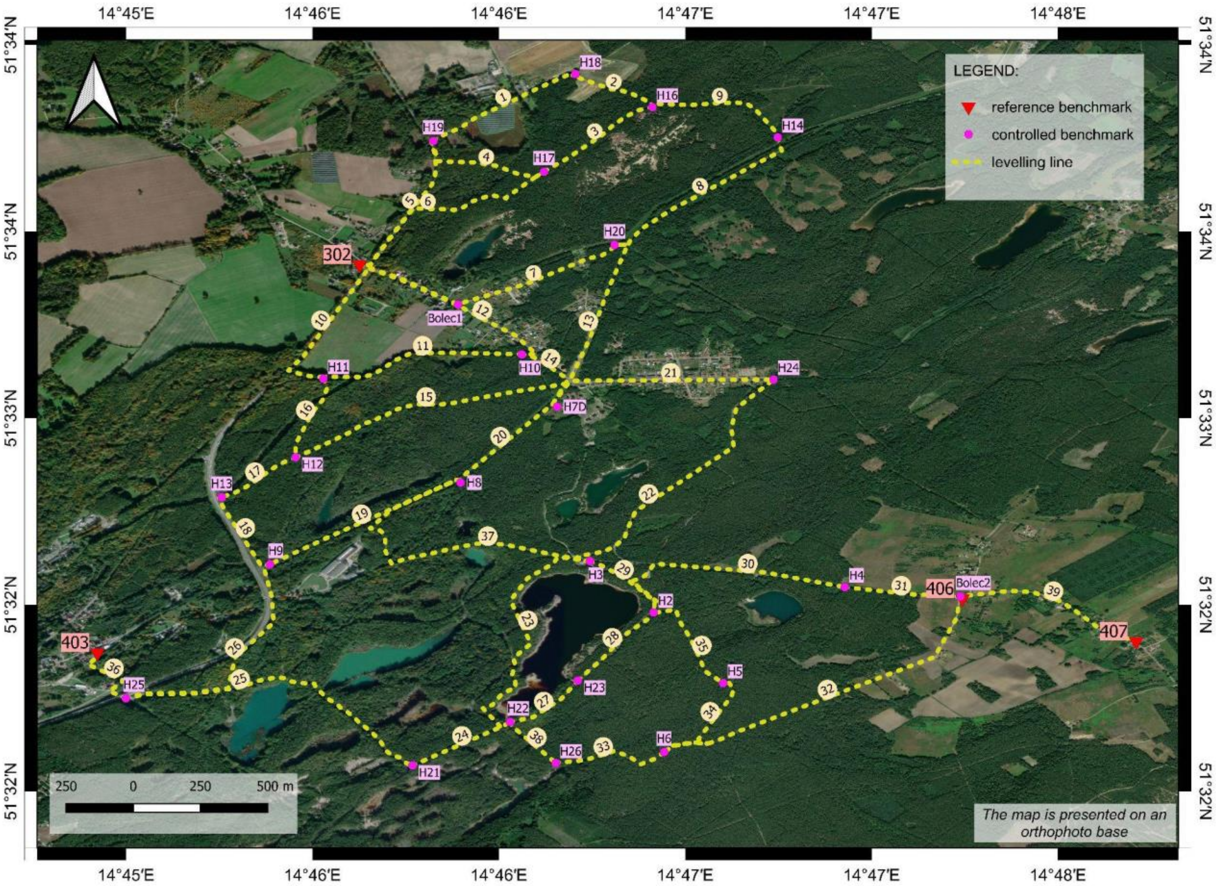

Fig. 4. The geodetic control network

3.2. Levelling measurements

Measurements in the grid were conducted with DiNi 0.3 Trimble code levellers, using precise code invar rods. The measurements were characterised by an accuracy of 0.33 mm/km. Each campaign included height measurements of the controlled points. The levelling campaigns were part of two National Science Centre projects (no 2019/33/B/ST10/02975 and no 2021/43/B/ST10/02157). After setting-up of the network in May 2020, six measurement campaigns were carried out. The first measurements took place in September 2020 and act as reference for subsequent campaigns carried out in yearly intervals with the exception of year 2021 when two measurements were conducted in Spring and in Autumn (Table 1).

Table 1. Dates of levelling measurements carried out in the study area

Campaign Number	Date
0	09/2020
1	04/2021
2	10/2021
3	05/2022
4	09/2023
5	09/2024

3.3. Calculation of Ground Movements

The collected levelling data were compiled using the following software: Excel, GeoNET and QGIS. The first stage involved the collation of the measurement data. This was followed by a validation check of the results by verifying that the deviation values ρ for the selected measured sections in the main and return directions did not exceed the permissible value. The maximum deviation was calculated as 0.4 x √L, where L is the average length of the levelling sections in kilometres [46]. The next step was to check the closure of the 12 levelling loops, which included controlled points. To calculate the maximum loop closures, the formula 1.5 x √L was used [46].

Further data processing was carried out in the GeoNET 2006 software (http://www.geonet.net.pl/?informacje/oferta/geonet.html). In the first stage, an analysis of the stability of the reference benchmarks was carried out. For each measurement campaign, the stability of the reference benchmarks was assessed relative to the heights of points obtained from the initial measurement (no. 0). With their confirmed stability, these benchmarks were held fixed during the network adjustment to ensure the precision and reliability of the entire network alignment. Given the absence of significant deviations, it was resolved to utilise all four reference points. Subsequently, the vertical ground movements of the controlled points were determined using the differential method, which permitted the consideration of alterations to the geometric structure of the network between the original and subsequent measurements (http://www.geonet.net.pl/gfx/opliki/18/geo_spec.htm). These results were calculated in two ways presented in Table 2, i.e. between the initial campaign (0) and subsequent measurements, and between consecutive campaigns, e.g. 0-1, 1-2, 2-3, 3-5 and 4-5.

Table 2. Dates of measurements with dates of periods of ground movements calculation

Periods	Dates	
	From	To
0-1	09/2020	04/2021
0-2		10/2021
0-3		05/2022
0-4		09/2023
0-5		09/2024
1-2	04/2021	10/2021
2-3	10/2021	05/2022
3-4	05/2022	09/2023
4-5	09/2023	09/2024

3.4. Presentation of the Measurement Results

The results of ground movement calculations were compiled and presented as descriptive statistics in tables and graphs. The calculated statistics include: the mean registered ground movements in the study area, ground movements registered in controlled points between the first, last and the subsequent campaigns, as well as the greatest ground movements that were observed. In addition, the movements registered in controlled points were presented as maps presenting direction and magnitude of calculated height changes against the background of the extent of known mining in the study area. Finally, we proposed visualisation of ground movements with Voronoi polygons as an alternative to the classical isoline presentation. Isolines of ground movements are determined with continuous interpolation methods such as spline functions, inverse distance weighted or polynomial [47]. In our approach we used a discontinuous interpolation method, the Voronoi diagrams, also referred to as Thiessen polygons, that divide a two-dimensional plane into distinct regions based on a set of designated reference points. A Voronoi diagram defines regions based on the closest neighbourhood of reference points, such that each point in a region is closer to its centre than any other centre in the diagram and represents the same value [48]. The maps were prepared in free and open source QGIS software and in the Python environment.

4. RESULTS AND DISCUSSION

The mean ground movements calculated as the arithmetic average for all controlled points between measurement 0 and subsequent campaigns (1 to 5), and between consecutive campaigns, i.e. 0-1, 1-2 and so on, are presented in Table 3 and graphically in Fig. 5. These values provide a generalised situation of elevation changes and serve as a preliminary step in the analysis. However, they do not fully account for the spatial variability of ground deformations in the study area. This is presented in later parts.

Table 3. Mean ground movements in the study area in each period and average error of the levelling network measurement

Periods	Dates		Mean ground movement [mm]	Average measurement error of the levelling network [mm/km]
	From	To		
0-1	09/2020	04/2021	2.73	±1.13
0-2		10/2021	1.70	±1.01
0-3		05/2022	2.54	±1.04
0-4		09/2023	-0.99	±0.91
0-5		09/2024	-0.93	±1.03
1-2	04/2021	10/2021	-1.02	±1.25
2-3	10/2021	05/2022	0.84	±1.16
3-4	05/2022	09/2023	-3.53	±1.06
4-5	09/2023	09/2024	0.06	±1.05

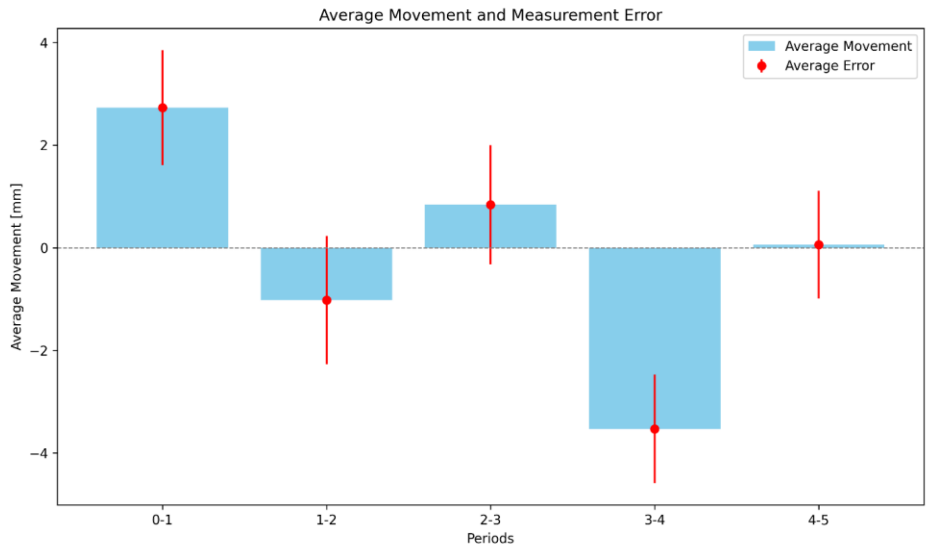

Fig. 5. Mean ground movement in the study area between consecutive campaigns calculated from levelling network measurements

The mean maximum ground movements range from -3.5 to +2.7 mm with maximum error of ±1.25 mm/km. This statistic presents a generalised view of the elevation changes that does not take into account local differences that can exist between various parts of the study area subjected to underground, open-pit or combined mining. However, these values can be an indication of phenomena taking place in the entire study area. It is worth noting that cumulative mean ground movements had positive direction (elevation) between 9/2020 and 5/2022 that changed to negative direction (subsidence) between 9/2020 and 9/2024. This can be further differentiated when mean ground movement values between consecutive campaigns are analysed.

The histogram in Figure 6 illustrates the ground movement values for the main controlled points between period 0 and the subsequent measurement campaigns (1 to 5). In period 0-1, uplifts dominate, particularly at points H14, H2 and H16, where they reach values of +18.91 mm, +12.96 mm and +7.21 mm, respectively. In the 0-2 period (first full year cycle between September 2020 and October 2021), the elevation increase is still observed, with points H14 and H2 reaching +13.03 mm and +8.74 mm respectively. At the same time, the first signs of subsidence appear in the location of point H26, where the change is -2.0 mm. In the period 0-3, a more differentiated character of movements can be observed. There are subsets of controlled benchmarks, such as: H14 (+17.57 mm), H16 (+5.95 mm), H21 (+4.69 mm), H2 (+13.00), H8 (+5.15) and H9 (+3.50) where the change in height compared to the initial measurement campaign is positive (elevation). However, 2 controlled points, H21 and H24 now show subsidence, with values of -4.82 mm and -5.58 mm respectively.

In the next 0-4 period (September 2020 to September 2023), the change to the subsidence trend becomes more apparent, with 8 points registering downward movement in relation to the initial campaign. The greatest values were registered in points H24 (-5.58 mm) and H10 (-5.09 mm).
This trend continues in the last period (0-5), where 7 points show subsidence greater than 2 mm with point H24 reaching -8.06 mm and point H10 -6.02 mm.

Taking into consideration that the period 0-1 spans the time from September 2020 to April/May 2021 with 3 months between the stabilisation of network points and the first measurement campaign there could be an unknown factor influencing the ground stability of seasonal character.
Apart from the observed change of the general trend from elevation to subsidence in the study area between period 0-3 and subsequent observations, local variability is also identified. Some controlled points showing statistically insignificant movement compared to the other ones, e.g. H3-H5, H12, H17 and H23. This spatial variability highlights the complexity of changes occurring in the post-mining area. The changes of benchmark heights, campaign to campaign, have been presented in Figure 7. In contrast to the cumulative data shown in Figure 6, this graph highlights the changes occurring between successive periods. In particular, periods 1-2 and 3-4 show clear subsidence at most of the controlled points, particularly evident at points H14, H16, H2 and H21. In the period 2-3 uplift is observed on most of the controlled points, however it lesser than previously noted. In the next period 3-4 we can again notice general subsidence. Point H2 registered displacement of -13.84 mm and other points, such as H16 and H21, also show significant subsidence. In contrast, in the last analysed period (4-5), the deformation dynamics are more varied, with some points, such as H14, showing positive displacements (+6.32 mm), while others, such as H24 and H10, are still characterised by pronounced subsidence, reaching values of -8.06 mm and -6.02 mm respectively. These results point to the local variability of deformation processes, and may suggest the influence of changing hydrogeological conditions on seasonal variations in the height of controlled points and demonstrate the need for continued monitoring and detailed analysis.

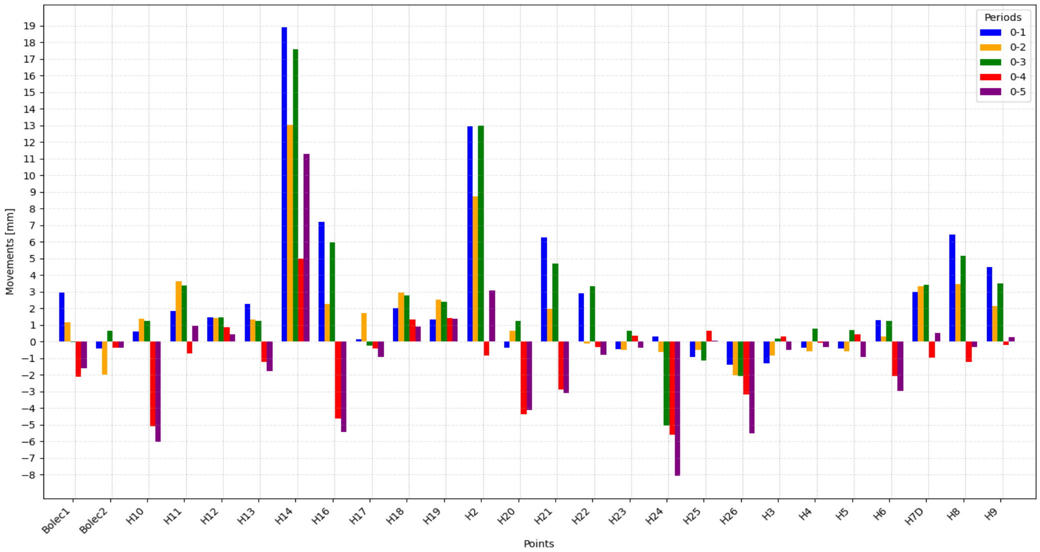

Fig. 6. Histogram of the movements for each of the controlled points between initial (0) and subsequent levelling measurements (1 to 5)

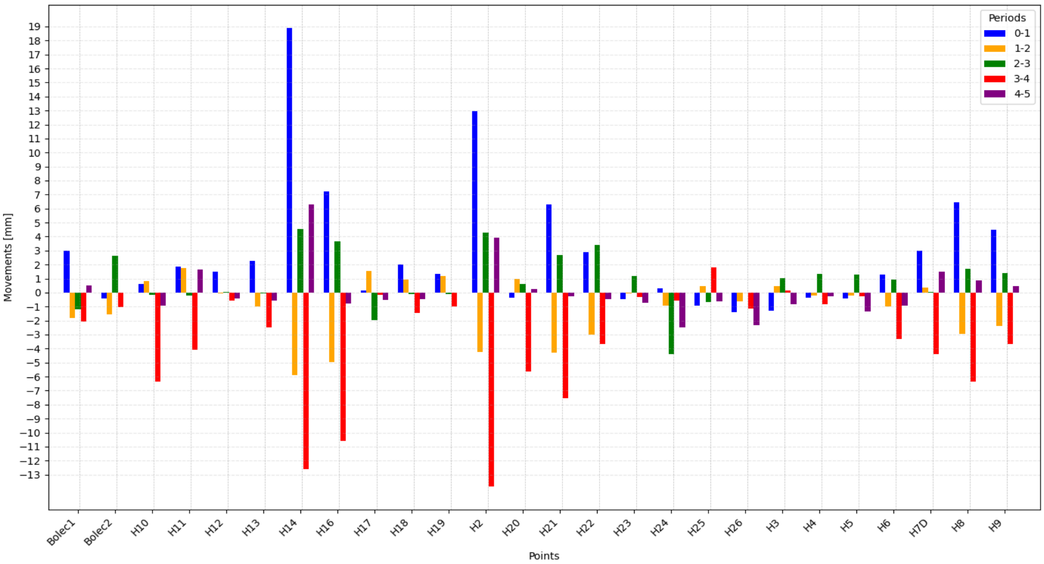

Fig. 7. Histogram of movements for each of the control points between subsequent levelling measurements (0 to 5)

The spatial context of these movements in relation to the known extent of underground and open-pit mining, as well as outcrops of lignite known locally as gizers is shown in Figures 8 and 9. The direction of the arrows indicates the type of change: upwards for uplift (shown in red), downwards for subsidence (shown in blue). The size of the arrow is proportional to the value of the movement, according to a fixed scale factor. The smallest movements, predominantly within the range of measurement error, occurred in the western part of the study area, which is on the edge of the post-mining zone, and probably beyond the range of its influence (benchmarks H11, H12, H13, H19). The points located in the southern part of the levelling network are in the groundwater drainage area of the Nysa Łużycka river valley. The controlled points in the central and northern part are located in a zone of combined underground and open-pit mining (H7D, H8, H10, H16, H17, H18, H19, H20) that was the most intensely transformed in the course of mineral excavation. Point H2 is located on the edge of former open-pit now the largest anthropogenic lake in the area. Point H14 is situated in rea of former underground mining and occurrence of gizers.

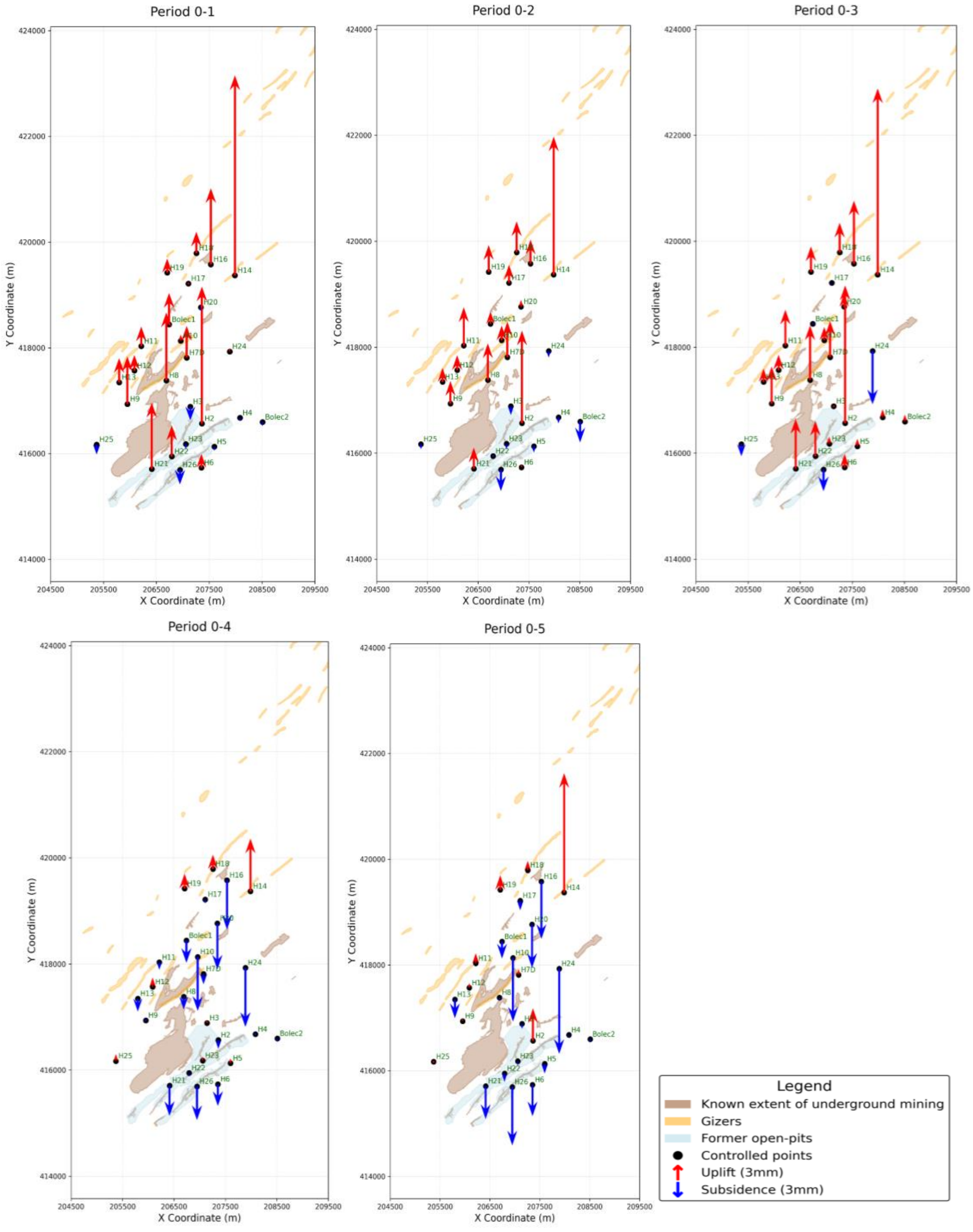

Fig. 8 Maps of ground movements observed in controlled points between initial (0) and subsequent levelling measurements (1 to 5)

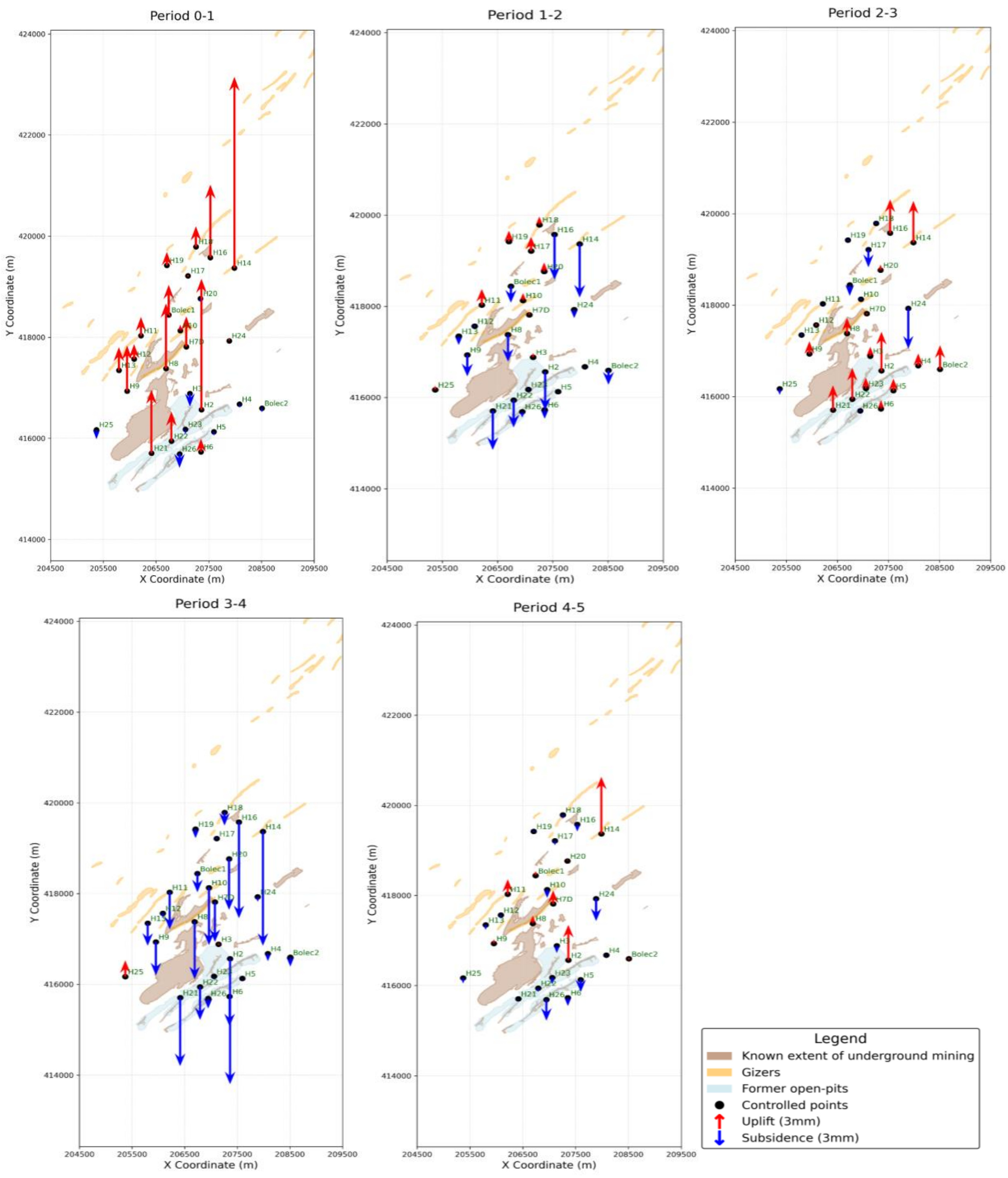

Fig. 9. Maps of ground movements observed in controlled points between subsequent levelling measurements (0 to 5)

The final visualisations utilise Voronoi maps (Figures 10 and 11), prepared with the approach presented in part 3.4. These maps are an alternative presentation of the spatial context to the one shown in Figures 8 and 9. The controlled points with their observed values of ground movements were used as the centres of Voronoi cells. We defined 5 classes:
- statistically insignificant for movements of -3 mm to 3 mm (grey),
- statistically significant for movements of -10 mm to -3 mm (light blue),
- statistically significant for movements of 3 mm to 10 mm (light red),
- double statistically significant for movements less than -10 mm (blue),
- doubly statistically significant for movements above 10 mm (red).
The Voronoi maps also contain information on the spatial location of gizers, underground and open-pit mining, and can be used to analyse the seasonal and local variations in ground movements observed in the study area.

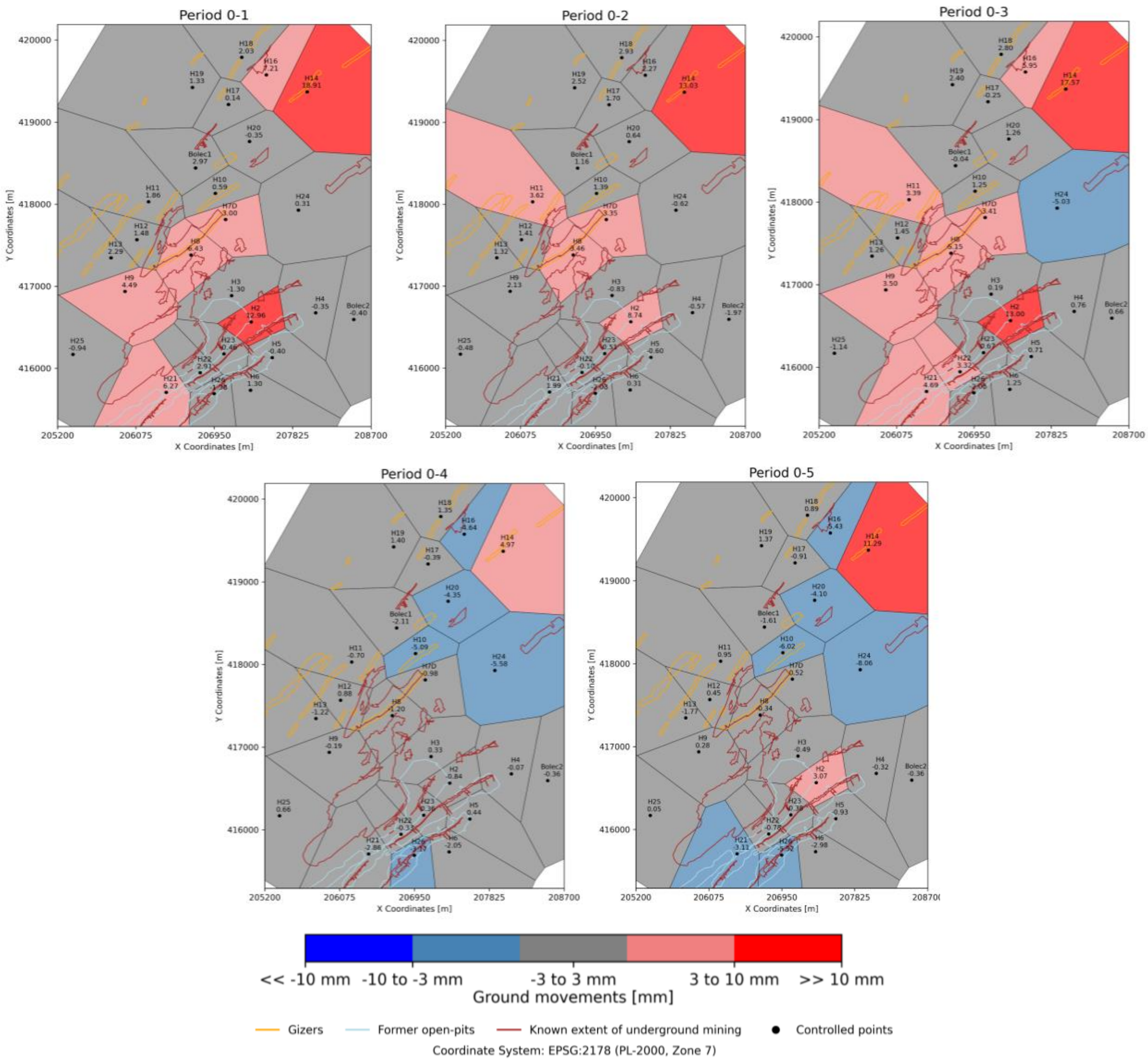

Fig. 10. Maps of Voronoi diagrams showing movement values between initial (0) and subsequent levelling measurements (1 to 5)

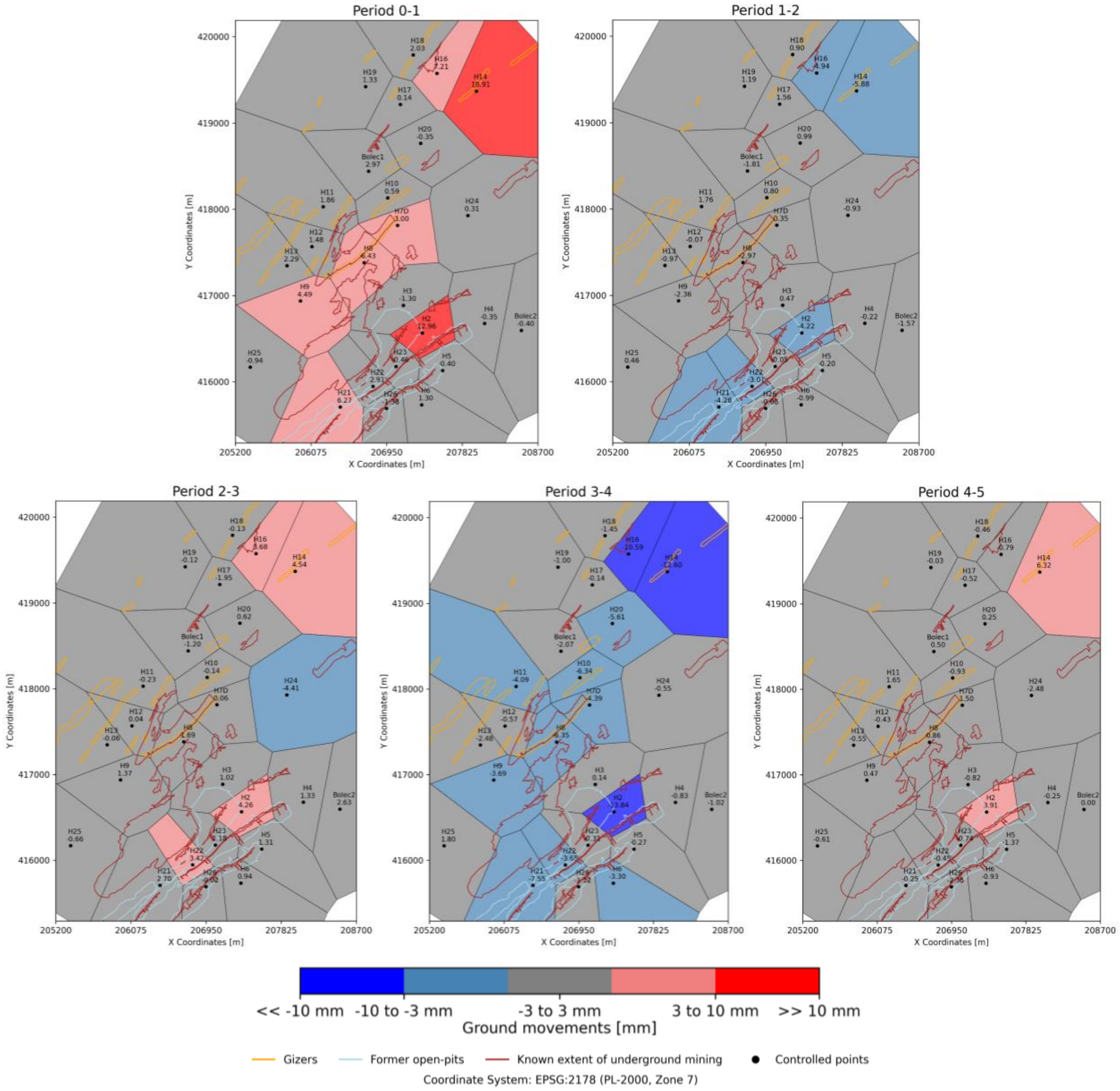

Fig. 11. Maps of Voronoi diagrams showing movement values between subsequent levelling measurements (0 to 5)

Table 4 contains a list of controlled points with the greatest ground movements observed in the entire study period. The greatest values were observed on controlled points: H10 and H24 with subsidence in the range of -5.09 to -8.06 mm, and on controlled points: H2, H8, H11, H14, H16 with elevations in the range of +3.62 to +18.91 mm. Location of these benchmarks in the levelling network and their spatial distribution in relation to the known extent of underground and open-pit mining together with graphical representation of the observed movements is presented in Figures 8 and 9.

Table 4. Controlled points with the greatest observed ground movements values between period 0 and subsequent periods

Periods	Dates		Name of the control point	Maximum Movement [mm]	2*MdH [mm]
	From	To			
0-1	09/2020	04/2021	H14	18.91	1.88
			H2	12.96	1.45
			H16	7.21	1.86
0-2		10/2021	H14	13.03	2.13
			H2	8.74	1.55
			H11	3.62	1.84
0-3		05/2022	H14	17.57	2.05
			H16	5.95	2.00
			H8	5.15	1.50
0-4		09/2023	H24	-5.58	2.32
			H10	-5.09	2.20
			H14	4.97	2.76
0-5		09/2024	H14	11.29	2.70
			H24	-8.06	2.30
			H10	-6.02	2.18

The presented preliminary analysis of the results of levelling measurements spanning a period of 5 years (9/2020 - 9/2024) shows that the post-mining study area is not stable over 50 years after the end of lignite extraction with significant, exceeding twice the error of their determination, ground movements. We have observed two processes. The first one is indicated by ground movements registered on benchmarks throughout the study area and potentially associated with seasonally changing groundwater table in the entire study area, a process potentially related to change of climate. The other, indicated by significant upward and downward movements, is associated with potential effects of former mining activity and observed locally on selected benchmarks. Both of these phenomena require further investigations, e.g. with spatial regression approach and taking into account precipitation, groundwater table readings, and historical records of mining activity.

We have selected precise levelling as the most appropriate method providing data on ground movements in this complex study area. An alternative approach could be provided by satellite radar interferometry (InSAR) as it allows observing ground movements in the line of sight (LOS) or, after signal decomposition, as vertical and horizontal (W-E) components with greater spatial and temporal resolutions. Such applications were successfully demonstrated for post-mining fields, e.g. abandoned mines on the French-German border [1], hard coal mines in Wałbrzych (Poland) [18], abandoned Konrad copper ore mine in Poland [11], coal mining area Lugau/Oelsnitz in Germany [35] coal fields in Belgium [4]. Some studies combined InSAR and levelling observations [1, 28, 29, 35, 49]. However, the study areas reported in these publications were characterised with more suitable land use types that allowed to effectively use satellite radar interferometry techniques such as Persistent Scatterer Interferometry (PSI) that relies on identifying stable objects (e.g., buildings) that consistently reflect radar signals over multiple satellite passes [50] or SBAS InSAR that utilises a set of SAR images with small temporal and spatial baselines to minimize decorrelation and noise and provides better results than PSI in areas with distributed scatterers (e.g. soil, vegetation). Due to the unique characteristics of our area of interest covered predominately with mixed forest, numerous surface water bodies and limited presence of low vegetation, bare soil (on some waste heaps) and build-up areas, application of satellite radar interferometry did not yield useful results. Thus, data on present-day ground movements is limited to the locations of the controlled benchmarks. This approach has been applied by others who also relied on results of repeated levelling campaigns for monitoring [51] or theoretical modelling of residual ground deformations [52]. Spatial interpolation techniques, such as inverse distance weighted, spline, kriging are commonly used to obtain a continuous information [35, 47, 53]. In our study we have adopted a different approach and developed ground subsidence maps applying a discrete interpolation method (Voronoi cells) that divides the space into convex polygons where each polygon corresponds to one data point (controlled benchmark), and all locations within the polygon are closer to that point than to any other polygon in the analysed space. Thus, the value at any location inside a given polygon is equal to the value of the nearest data point (center of the respective Voronoi cell) as no averaging or weighting of surrounding points is performed. In the result we obtain a ground movement surface that is not smooth as in the case of continuous interpolators but piecewise constant and sharp boundaries at the edges of computed polygons. These results provide a preliminary indication of the processes occurring in the study area and form a foundation for further studies with additional data, topographical, meteorological and describing the now ceased mining operations.

5. CONCLUSIONS

The study conducted a detailed analysis of the continuous ground movements in the post-mining area of the "Babina" mine, using precise levelling measurements. It is the first study of its kind since the end of mining, and the results indicate that, despite more than 50 years having passed since mining ceased, the area remains active in terms of ground movements. The preliminary analysis of these results points to the complex nature of the post-mining area subjected to both underground and open-pit mining and complicated character of the potential processes taking place in the study area that impacts the observed benchmarks. Both subsidence and uplift of land surface were observed that vary both seasonally and between various parts of the study area with greatest movements reaching 19 mm.

The observed deformations can have a variety of causes. On the one hand, they can be attributed to seasonal changes of the reconstructed groundwater table due to climate change factors. On the other hand, local secondary effects related to past mining activities may also influence the formation of ground movements. These could potentially trigger further sudden formations of sinkholes in zones of former shallow underground mining.

The research demonstrates the importance of systematic monitoring of post-mining areas. The precise levelling remains the most reliable method for detecting vertical displacements due to its high accuracy and ability to capture even small-scale movements. However, long GNSS observation sessions at controlled points can serve as a complementary approach, particularly when measurement intervals are sufficient to capture ground movement trends over time. The precise levelling method used has proved effective in detecting small-scale ground movements. One of the main limitations of the presented study is the discrete nature of the levelling measurements constrained to the controlled benchmarks. This makes it difficult to obtain continuous ground movements over the entire study area. Further studies could use continuous spatial interpolation methods. Satellite radar interferometry (InSAR), with greater spatial resolution of the ground deformation field and greater frequency of data acquisition could provide data for better understanding of the processes. However due to the land cover characteristics of the study area its application is constrained by low coherence and low number of persistent scatterers.

The complexity of the observed processes requires further research, taking into account not only historical records of mining activity, but also information on hydrogeological and meteorological conditions.

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