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A Multidisciplinary Investigation of an Abandoned Old Mining Area Which Has Been Affected by the Combined Influences of Salt Karst and Human Exploration Activity

Zbigniew Szczerbowski * and Rafał Gawałkiewicz

Faculty of Geo-Data Science, Geodesy, and Environmental Engineering, AGH University of Krakow, al. A. Mickiewicza 30, 30-059 Kraków, Poland; gawalkie@agh.edu.pl
* Correspondence: szczerbo@agh.edu.pl; Tel.: +48-12-6172256

Abstract: The authors discuss a case that is full of examples of the problems faced by civil engineers whose task is to develop areas in the face of natural, technological, or post-mining hazards. The study area is in the central part of Inowrocław, a town located on a massive salt dome of Zechstein salts. A strong deformation zone expanded in its upper part; this was caused by a natural process (related to so-called salt karst) and by mining activities that occurred in the past, creating a problem with regard to any potential spatial development in the town. The authors show a combination of data obtained using gravimetric and geodetic methods, which helps us to assess the geohazard risk. These include remote sensing data, which can be used to evaluate displacements of the ground surface. The authors used an approach that they term the Elevation Difference Method. This consists of determining displacements between ground surfaces: estimated on the basis of remote sensing data and on the basis of the historical data, when mounted measurement points (and remote sensing data) did not exist. The authors discuss the results in the light of the geological background. Within the area of the study, the displacements of the positive values dominate. The displacement occurs at 6 mm/yr on average and indicates diapiric uplift movement. The results are important for the town authorities for planning and development and for infrastructure management.

Keywords: geohazards; sinkholes; gravimetric measurements; leveling; LIDAR; mining

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1. Introduction

The geology of the North European Plain is distinguished by the occurrence of numerous salt structures [1,2], which are usually associated with tectonic deformations and sometimes the manifestation of active diapirism, which generates some problems for the stability of the ground surface [3–11]. Ground instability (subsidence, ground collapse, sinkholes) is caused by intense underground leaching (subrosion) and by the development of karst phenomena. These phenomena, in turn, are associated with salt tectonic sinkholes, which are serious geological hazards, especially when they occur in urban or built-up areas. Human-related actions (mining, construction of new buildings, groundwater pumping and infiltration, interventions in the hydrological regime, etc.) may lead to the formation or the re-activation of sinkholes at the surface [5–7].

To avoid catastrophic effects, appropriate urban planning is crucial to reduce the environmental and economic impacts that accompany both natural and human-induced geohazardous events. Thus, local authorities and countries have developed proper policies and strategies which aim to effectively manage hazard risks, which are defined along with the other terms, in general urban ordinance plans.

The other aspects deal with assessing the potential geohazards and with managing the risk. They are associated with the precise mapping of the areas affected by ground instability (especially the presence of active sinkholes) and the quantitative depiction of the ground instability (displacements, kinematic pattern, and spatial–temporal distributions).

The first aspect is related to geophysical research, which enables the identification of underground sources of danger, and the second aspect is concerned with surveying methods for investigations of ground displacements.

Detailed field surveys are essential for a more precise mapping of the sinkholes to confirm the existence of any buried sinkholes or underground caverns, and in fact they apply both the geophysical and the surveying methods. Such a multidisciplinary approach to shallow-geohazard research was applied in the town of Inowrocław, central Poland.

The key issue raised by the authors was the manner in which we could arrive at an assessment of displacements in the abandoned area of the former borehole exploitation. While geophysical research and historical documentation of old sinkholes and mining excavations seem to be sufficient for this area, there has been no recognition of surface deformations for decades. This has been the result of the loss of geodetic benchmarks many years ago, which was at the heart of the observation network established for the assessment of mining damage in the first half of the twentieth century.

The task of evaluating surface movements for this region was performed based on data from archival maps, which included height spots and modern remote sensing measurements (LIDAR).

Models of terrain surfaces and their differentiations are widely used in various fields aside from Earth sciences [11]. However, so far, there has been no description of the recent activity of salt dome movements in the European Zechstein salt formation with the use of high-resolution remote sensing data.

The authors have determined the displacements between ground surfaces, which are estimated based on remote sensing data and historical data. This approach, which the authors have named the Elevation Difference Method, is not revealing in itself, but this term has a technical sense here. The authors formulate a terminological convention, i.e., they agree with the readers that they will replace the entire long description with this term of their choice in the form of a possibly short expression. This is why the term has been created.

2. Geoenvironmental Setting

The area of Inowrocław is in fact a post-mining area, where the last mining operations were carried out over 30 years ago, but there are still ground deformations that can be detected via surveying methods. This area, which is located just over the salt diapir—one of the many in the North European Plain—has become a survey field for several generations of geologists and geophysicists. Thus, the salt structure of Inowrocław has been the subject of comprehensive studies for several generations of geologists and geophysicists. These studies were carried out based on the needs of geological exploration and mining works in the past. Nowadays, these studies are conducted for geohazard assessment, which is important to the community in terms of planning and development, as well as for infrastructure management. While the large number research studies undertaken over the past one hundred years is awe-inspiring, there are still key knowledge gaps to be filled. A particularly important issue is the need to obtain information on the characteristics of ground surface displacements in the area of the old borehole mining in the western part of the town. Hence, a large area of the site is excluded from built development.

Potential reasons for the observed displacements, which have positive and negative values, are as follows. Firstly, there has been suberosional deposition of soluble minerals; secondly, a diapiric uplift movement of the dome has been observed; and lastly, we are left with the post-mining effects of abandoned mine workings. Although they are only small vertical displacements occurring at the rate of several mm a year, the displacement of negative values should be assumed as the result of karst development, which is one of the most hazardous phenomena that can cause the collapse of the ground surface. A combination of the aforementioned sources affecting the stability of the ground surface generates quite complex spatial characteristics of ground movements, and their suitable analysis and interpretation requires in-depth knowledge of the underground conditions (geological setting, geotechnical properties, hydrogeological regime, localization of natural or post-mining cavities, etc.).

The geological structure of the Inowrocław salt dome is one of many salt structures which appear in the Polish part of the North European Plain (mostly in the Kujawy region). It has clearly affected the surface topography. An example of this is the fact that the town that has developed right above the salt structure is also located on a small hill that is only 12 m high, yet quite clearly stands out in the flat area of Kujawy.

The depth of the salt surface in Inowrocław is one of the shallowest salt structures in the Polish province of Zechstein salt formation: in some areas, its gypsum cap rock lies only a few meters below the surface. The gypsum cap is at a depth of 6–221 m, while the top surface of the salt structure is situated at a depth of 122–272 m (Figures 1 and 2).

The local geology follows a simple pattern with a salt dome which consists of a core of salt and an envelope of surrounding strata. The Inowrocław salt dome consists of Zechstein salt sediments sloping almost vertically, and the dome is also covered by steeply deposited Jurassic sediments. Its overburden consists of Quaternary sediments, and in the northern part of the deposit, these are also joined by strata. The Jurassic formations surrounding the deposit consist of sand deposits in the western part and deposits of the Lower Jurassic sandstones with poor diagenesis, while in the eastern part, in the middle and in the Upper Jurassic formations, we find marls, limestones and dolomites. Quaternary formations with a thickness of 3 m to 47.5 m are represented by unsorted glacial sediments (glacial till), glacial sands, and gravel [12–19].

The salt series of the deposit consists of alternating seams and layers of pure rock salt, salt contaminated with clay and anhydrite, anhydrite and so-called zuber rocks (argillic and marly rocks with dispersed blocks of different types of salt).

Thanks to the intensive drills of many boreholes, the upper part of the dome has been relatively well recognized geologically, though geological exploration reached a depth of approx. 3000 m, while the lower part in the depth range of 3000–6000 m was not explored at all [10–13]. The maximum depth of the salt structure is not known (the deepest borehole of 3000 m failed to reach its bottom) but it is presumed that the dome began its development at a level of 4500–6000 m below the surface. It should be added that mining operations have penetrated the deposit only to a depth of 638 m [17,18].

The cap rocks (gypsum and gypsum–clay rocks) covering the upper part of the salt dome are of a heterogeneous formation and appear as a disorderly, uneven mass, which may be interpreted as being a secondary formation and a residue of the underground leaching of soluble rocks [18]. It features diversity in lithological development: a gypsum cap developed over the outcrops of the salt series (mainly in the northern and western parts of the deposit), while a clay–gypsum cap with a small amount of gypsum developed over the outcrops of zuber (eastern part of the deposit). In the gypsum cap, as a result of the flow of groundwater, karst phenomena occur in the form of fissures, pits, and caverns, and these phenomena have also manifested themselves in the form of sinkholes on the terrain surface (these occurred in the past, before the era of mining activity). The localizations of these documented sinkholes reflect this geological division: most of them are placed in the western part of the town (which is the area under discussion in this study).

The surface of the salt table is wavy and uneven, and it reminds us of the topography in the mountainous areas. It generally slopes to the south, but it is also more or less flat over a large area. In the northern and southern parts of the dome, the surface is more diverse, a result which should be associated with the activity of underground waters [13].

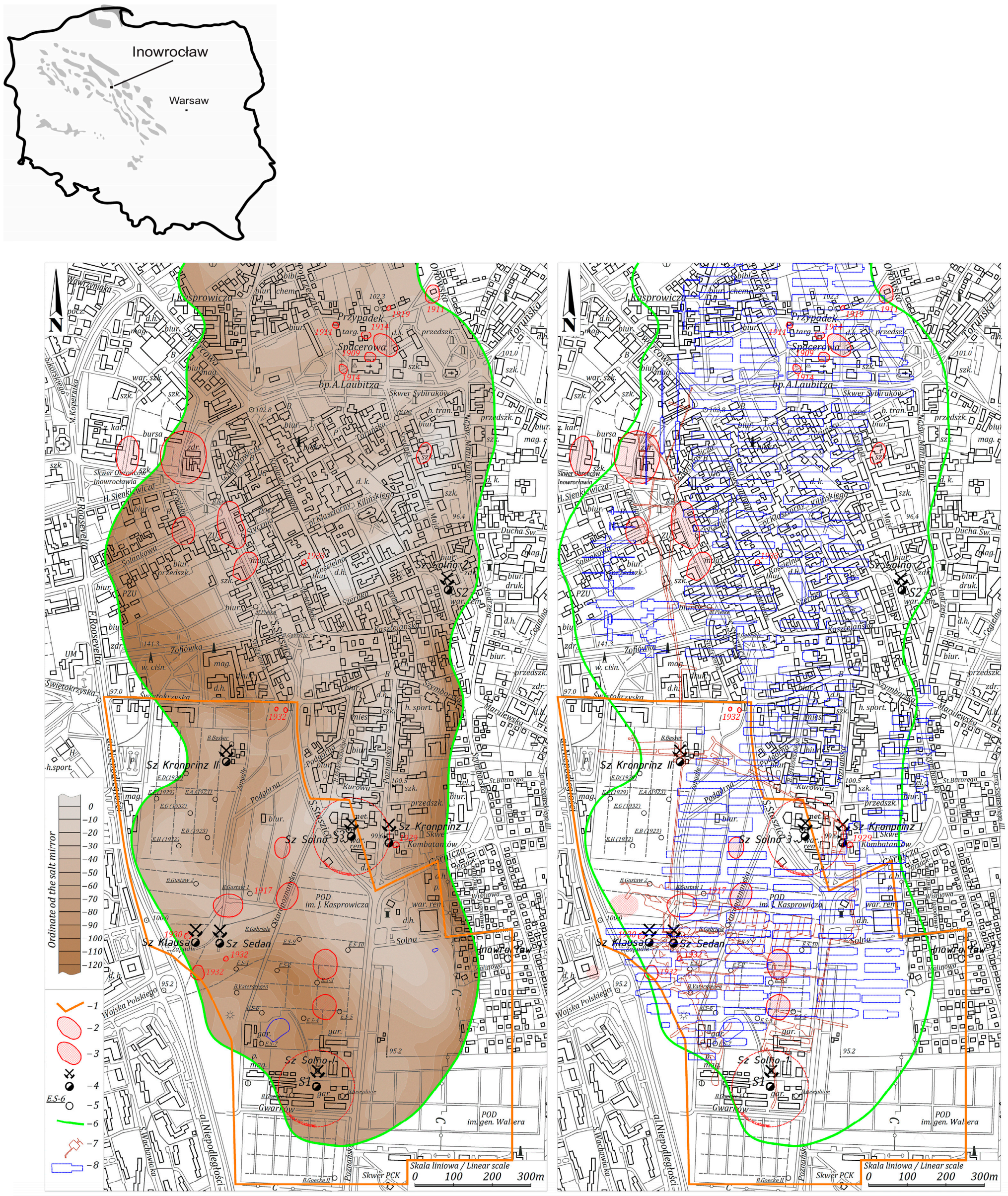

Figure 1. The map on the left: localization of the area under study and other Zechstein salt deposits in Poland. Hipsometric structural map of the salt roof of the Inowrocław dome and the Solno's workings, and old boreholes and mining shafts on the right (after [14], modified). The legend presents the signatures used on the map and their numerical designations; their meaning is as follows: 1—boundary of the area under study; 2—sinkholes that existed before 1861, according to W. Budryk [8,13]; 3—sinkholes that occurred after 1861, according to W. Budryk [13,18]; 4—abandoned mine shafts; 5—boreholes; 6—boundary of the salt dome at the depth of 470 m; 7—workings of the shallow mines from the beginning of the twentieth century; 8—workings of the Solno mine.

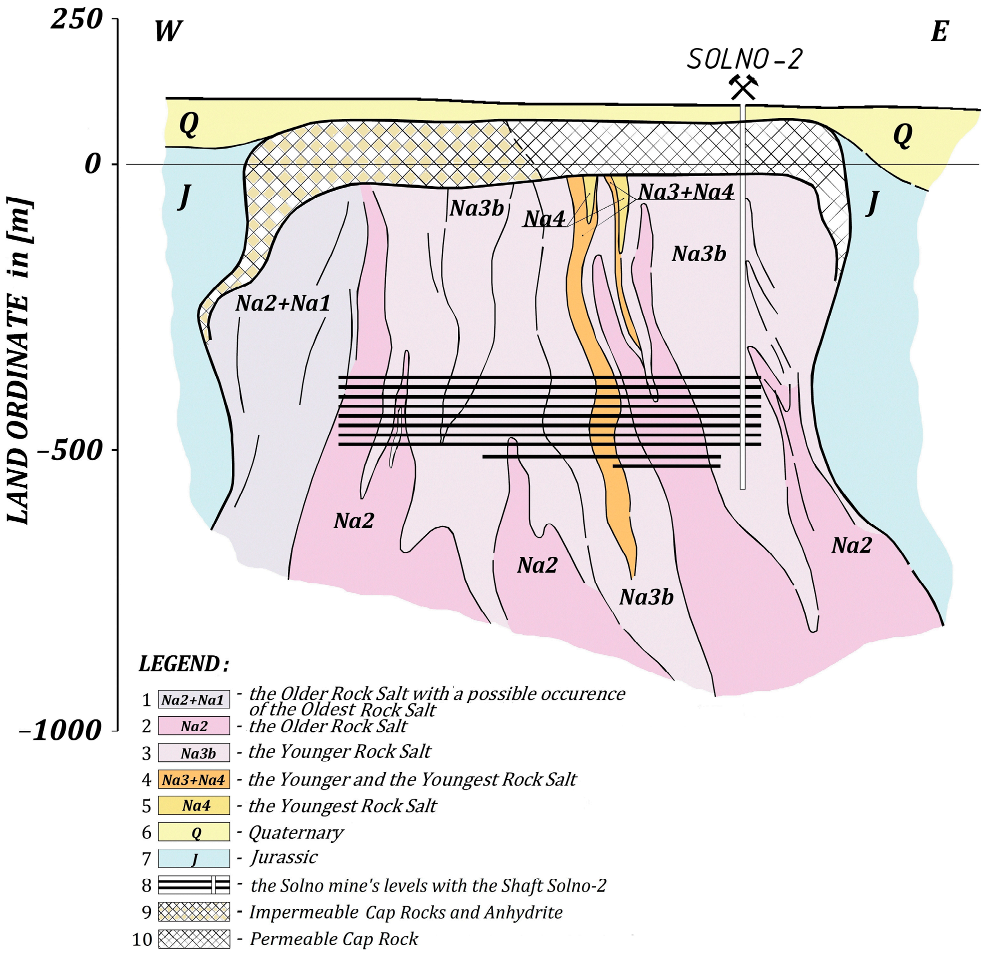

Figure 2. Geological setting and tectonics of Inowrocław salt dome (cross section after [16] modified).

Another characteristic feature of the deposit is its geometry; in the horizontal projection of the upper, well-recognized and thus geometrized part, the deposit shows itself in the shape of an ellipse with a longer, meridian-oriented axis, approximately 3 km long, and a shorter one of 1 km long.

Factors such as exploratory borehole drilling, followed by drilling mining and shallow underground mining and, most importantly, by intensive brine extraction, have disturbed the hydrogeological balance, causing an increased flow of water in the gypsum cap as well as in the deposit; the water circulation has greatly increased as a result [13–15]. In more recent times, more intensive leaching has taken place, which in turn has been reflected on the surface by the formation of numerous sinkholes.

The fact that within the area, individual aquifers have been connected has led to the assumption that for the purpose of considering the problems of the risk of water inflow to the underground workings, and also the problem of surface protection, there is in practice one aquifer that covers both the salt dome and the rocks surrounding it. Because of this assumption, it was thought that it is only mining activity that has caused the creation of numerous underground channels, through which water from mainly Jurassic formations began to flow to the cap, and then cleared the caverns and fissures within it.

Based on the observation of the distribution of sinkholes, it can be stated that there are certain directions, or more precisely, certain zones of tectonic disturbances.

The most elevated part of the deposit is in the central-eastern part, in which there are clay salts. These salts are the most resistant to leaching by flowing waters. From this area, the dome surface descends in all directions, but definitely more towards the west, then towards the south and east. This is the result of the lithology of the rocks that make up the interior of the dome, where the northern part is made up of older, pure salts with a minimum amount of anhydrite sand. They run south on the west side and pass to the east side in the middle of the southern part of the dome. Therefore, the runoff of underground waters on the diaphragm also runs from the north-west to the south.

The flow of water thus refers to the topography of the roof part of the dome. The almost horizontal surface of the salt table in the central part turns with a gentle slope into the inclined side surface of the dome in the eastern part, initially under the gypsum cap, and then reaches greater depths under the Jurassic rocks [13–15].

The southern and western parts are more morphologically diversified, especially in the area analyzed here. In the southern part, the roof part of the salt structure arcs into the sloping side surface of the dome. It does so similarly in the northern part, while in the western part, it turns into a vertically collapsing side surface.

Thus, it can be concluded that the topography of the dome's roof, its lithology, and hydrogeological conditions are interrelated and are determinants of both the terrain morphology and of the deformations in the area.

3. Mining, Non-Mining and Post-Mining Displacements—A Brief History of the Development and Monitoring of Ground Deformation in Inowrocław

In the more than 100-year history of exploitation of the salt deposit in Inowrocław, mining operations were carried out in different periods, using various methods of salt extraction [18]. The date of the beginning of the history of modern mining activity in the area of Inowrocław is 1871, when the Ost borehole revealed salt at a depth of 129.64 m. Salt was found in most of the boreholes drilled in subsequent years. As a result, two competing enterprises developed, operating in separate mining plants (Kronprinz mining field, Inowrocław Salt Mine, Kronprinz, years 1873–1888). This exploitation consisted of obtaining salt from brine pumped from boreholes [14,18].

This pioneering period in the history of salt mining in Inowrocław was short-lived, and its end was related to the existence of hydraulic connections between the wells exploiting brine and a significant reduction in the level of brine in the boreholes [13,15]. This led to the state-owned company deciding to establish an underground mine. As a result, the I shaft and underground excavations were sunk, and the encountered brine sources were captured. At the same time, underground mining works were carried out by a private mining company. The exploitation carried out at that time covered the roof part of the deposit and was aimed at obtaining brines from natural sources that existed in the crevices encountered. Ignorance of geological and hydrogeological conditions resulted in a violation of the natural water regime.

In the next stage (years 1878–1907), underground mining was started (southern area of the deposit), which was carried out in the roof part of the deposit (salt and gypsum exploitation), but brine was still being pumped by several shafts. This stage was completed when numerous sinkholes appeared at the ground surface and the underground excavations flooded and collapsed (1907). However, the economic pressure exerted by various chemical companies forced the continuation of mining exploitation. A new approach was applied: in the time interval of 1923–1941, a system of boreholes was constructed for the brine extraction [18].

Although the method of extraction (borehole mining) was modern for those times, there was no plan to expand the mining fields due to the limited possibilities for developing this exploitation. Therefore, the concept of exploitation in the conditions of an underground mine operating in an orderly and rational manner that would not threaten structures on the surface was relinquished. The decision to build such a mine in the southern part of the deposit was made as early as 1924. After ten years of preparatory work, which involved drilling a shaft and building a network of drifts, mining with a room and pillar system began in the depth range of 479–637 m in the new and modern Solno mine. The total volume of all the mining chambers (1500) amounted to 16 mln m^3. The subsidence process caused by salt mining in the Solno mine created a subsidence basin with a maximum depth of 35 cm [4,18].

This period of mining activity in Inowrocław lasted until 1986, when the planned liquidation of the mine took place and mining workings were finally flooded in 1991 [4,18]. The Solno Salt Mine, the last company operating in Inowrocław, was closed down and regular measurements of ground displacements were stopped. Thus, the history of mining in Inowrocław ended.

Surface deformations above the salt dome, in the form of sinkholes occurring in the town, were recorded even before the start of any mining operations, i.e., before 1871 [13,18]. There are no reliable data on these sinkholes from that time, apart from the documenting of their location.

After the catastrophic flooding of the first mine in 1907, sinkholes were formed mainly in the northern group, and from 1917 there was an increase in surface subsidence in the southern part of the dome [13]. These sinkholes usually have a circular or elongated shape with significant dimensions and usually almost vertical walls. The last sinkhole occurred in 2004, in the western part, and it was well documented. Thus, occurrence of sinkholes should be considered as a "genetic" feature of this area, because their cause is salt karst and voids associated with this phenomenon and is created in the dissolution process occurring in the cap of the salt dome.

4. Contemporary Studies on Deformations Induced by Old Mining and by the Natural Movements of the Salt Dome

Movement of the rock substance deep into the rock medium, which is induced by mining or by natural geological processes, causes an effect called deformation.

Deformation characteristics depend on many factors (geological, hydrogeological, mining, etc.). The concept of ground deformation can be related to the geological substrate or to the terrain surface. When connected with the terrain surface, the concept of deformation refers to geometrical changes in the topographical relief, while deformation of rock mass is a concept which usually refers to changes in the physical properties of the rock medium. They cause observable changes at the ground surface which may be determined via surveying methods. On the other hand, geophysical surveys are able to recognize and identify deformations occurring in the geological substrate that may also develop and be revealed on the ground surface in the future.

Identification of the effects of the phenomena and processes ongoing in the salt rock mass of the Inowrocław dome is a complex problem. These actions caused deterioration of geomechanical properties of rock mass and have presented a threat to objects on the surface. As such, this issue requires comprehensive research using various research methods. Such comprehensive research methods have been successively used over the years in some of the localities in the area of Inowrocław.

During the mining era, when intensive exploitation of the salt deposit was being performed, geophysical measurement works were carried out for the purpose of obtaining a reliable geological recognition of the salt structure, while geodetic works were carried out to assess the impact of mining exploitation. After the end of the mining operations, research works were carried out to assess the post-mining effects and also the effects of the natural processes (subrosion, uplift movements of the salt dome). Hence, in the years 2002–2005 and in 2018, surveying/geodetic (leveling, GPS/GNSS, tachimetric) and geophysical measurements (gravimetric, seismic, GPR) were performed [20–26]. The most valuable results for the city area were obtained thanks to the leveling and gravimetric measurements; however, among the last two methods, only gravimetric measurements were taken in the study area [23].

In the years 1968–1969 and 1980, gravimetric measurements were carried out in the area of the Inowroclaw salt dome [20]. In total, nearly 2000 points were measured along 74 profile lines (Figure 3). The initial aim of these measurements was to determine the boundaries of the salt structure on the basis of a gravimetric anomaly induced by a smaller unit mass of the salt rocks forming the dome than forming the surrounding rocks [20]. In the next stage, the basic task of the gravimetric work was to determine changes in the physical state of the rock mass [16]. These gravimetric measurements were carried out using SCINTREX 202 and SCINTREX 375 gravimeters. The established network consisted of nine local base points. The average error of a single gravity measurement amounted to ±0.023 mGal, and it was found that the mean square error of determining the Bouger anomaly was ±0.037 mGal [20].

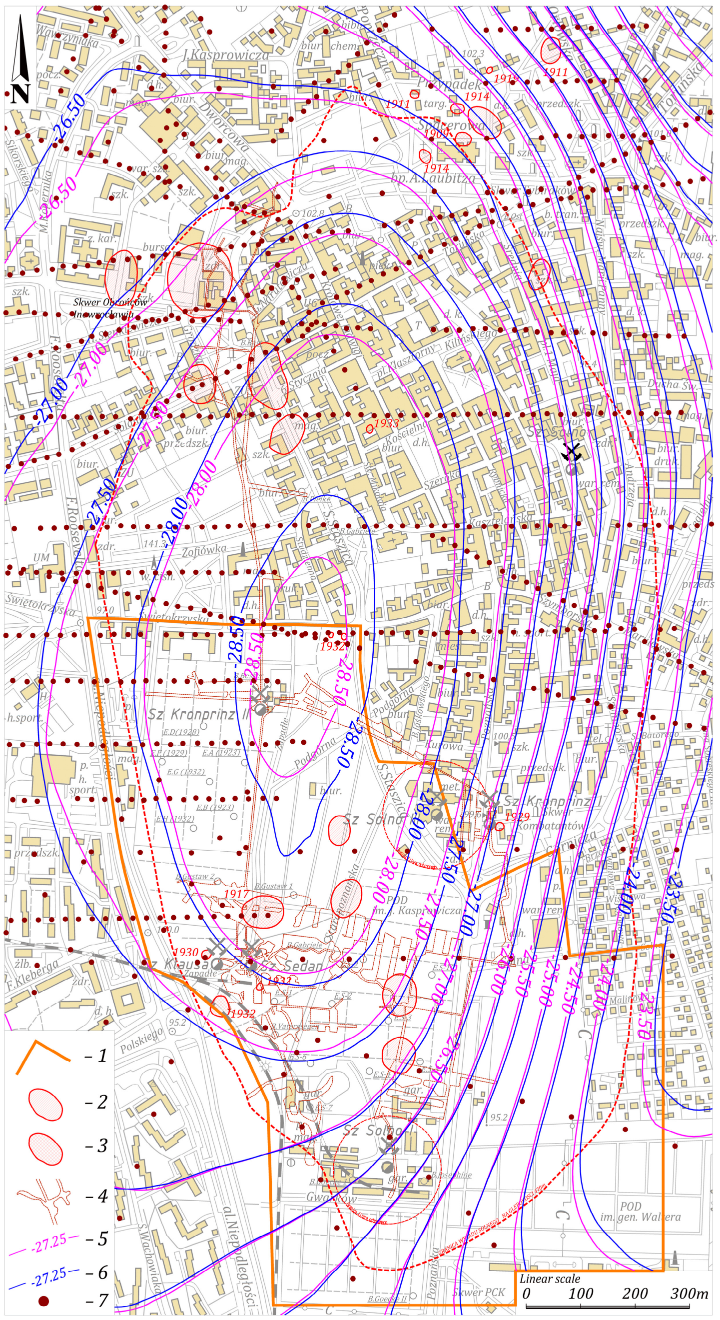

Figure 3. Distribution of gravity anomalies according to field measurements in 1968–1969 (cyan line) and in 1980 (blue line). The anomaly values are presented in milligals. The distributions based on the data obtained from [20]. The legend presents the signatures used on the map and their numerical designations; their meaning is as follows: 1—boundary of the area under study; 2—sinkholes existed before 1861 according to [18]; 3—sinkholes occurred after 1861 according to [18]; 4—abandoned mine shafts; 5,6—isolines of gravity anomaly; 7—points of gravimetric measurements.

The results of these works were reported in a technical elaboration [20] and they enabled the assessment maps of Bouger anomalies and maps of differential anomalies for the time interval of 1969–1980 (Figure 3). Figure 3 also presents the measurement points, along with distributions of the Bouger anomalies. The presented distribution of gravity anomaly isolines clearly corresponds to the geometry of the salt dome boundary in the horizontal projection (Figure 2). Small distances between isolines outline the fact that the exterior walls of the salt dome are steeply sloping, and the higher concentration of the isolines at the east side refers to the greater incline of the eastern wall of the dome. A difference in the distributions for the years 1968–1969 and 1980 was noticeable. The main reason for the changes is the gravitational effect induced by the underground workings of the "Solno" mine [20,27] and the subrosion and other hydrogeological reasons which changed a mass distribution in the geological substrate.

Despite the considerable depth at which the "Solno" mine was operating, the observationable changes in the gravity field were to be expected, taking into account the amount of the rock salt output which was removed from the interior of the rock mass. It should be noted here that rock mass under mining generates a gravitational effect. In the case of rock salt mass (unlike, for example, coal rock mass) this effect mainly consists of the gravitational impact of existing or closed excavations (while coal rock mass is also affected by caving zones and by fracture zones [28–32]. Mining activity causes the formation of voids and, as a result, a loss of mass in the rock mass, which results in the final gravitational effect being recorded as a negative gravity anomaly. Additional factors associated with the additional gravitational effect in the conditions of mining exploitation include rock mass deformations in the area of tectonic dislocations, and also hydrogeological changes in the rock mass [30]. The huge mass of rock salt extracted by the Solno mine induced a significant gravitational effect whose maximal value amounted to 0.3 mGal [27]. The liquidation of the Solno salt mine and the flooding of the workings with fully saturated brine reduced that effect by about 40% [27].

Due to the distances between the measurement points in surveys carried out in 1968–1969 and 1980, it was impossible to identify smaller anomalous structures (caverns, old sinkholes, etc.).

The microgravimetric measurements carried out in 2002–2005 in various areas of the town allowed for the determination of anomalous zones, which are associated with many phenomena including fault zones, old sinkholes, and underground suffusion [23]. These various phenomena have been the subject of many papers [27–32]. Gravimetric measurements which were obtained in the years 2002–2005 were carried out using the Scintrex CG-3 Autograv gravimeter. It is characterized by its ability to provide highly accurate measurements, i.e., approximately ± 0.010 mGal, with repeatability of results to within ± 0.005 mGal. Calculation of the adjusted values was carried out with an accuracy of ± 0.001 mGal [23].

The accuracy of the gravimetric measurements carried out in the period was much higher than those carried out previously, and the range of error of determining the relative values of gravity did not exceed ± 0.015 mGal [23], which was a value that equaled 1/20 of the expected maximal microanomalies caused by mining. Most of the measurements were obtained using the microgravimetry technique due to the fact that the basic research objective was the detection of weakness zones in the upper part of the rock mass, these weakness zones having been caused by mining/postmining and natural processes such as the creation or presence of caves, voids, or discontinuities.

It should be noted here that microgravimetry is a powerful means of approach for the detection of many small geological and anthropogenical bodies [28]. It is popular and is widely used, especially to map shallow subsurface karstic features. Studies on the principles of the microgravimetric technique have been published by many authors [28–32]. The majority of the town area was covered by points of local microgravimetric networks, and the results of the measurements have already been discussed in other papers [23,27].

One of the networks was established in the area of study in 2003. On the basis of the field measurements, the distribution of the Bouguer anomaly—a gravity anomaly which was corrected for the height at which it was measured and the gravitational attraction of the terrain—was determined. This distribution was approximated by a fourth-degree polynomial, obtaining the values of the regional field, which were assumed as a trend. Next, the determined trend was used as the basis for the analytical determination of the residual gravity field. That is to say that the residual anomalies, which are the effect of disturbances in the near-surface part of the rock mass, were estimated. For this purpose, the Griffin method, with a small radius for collecting data (50 m), was used, which made it possible to subtract the gravitational effect from the salt dome and extract the image of the residual anomalies (Figure 4). The distribution of the residual gravity anomalies varies in the area from −0.30 mGal to +0.3 mGal [23]. But the greater part of the microgravimetric network is characterized by residual anomalies of low values. Particular attention is drawn to the clearly marked anomaly in the area of the shallow underground workings which are a remnant of the historical mining operations which were carried out continuously at the border of the rock salt and the cap rock up until its catastrophic collapse in 1907. But subsequent borehole exploitation was also conducted in this area (Figure 4). The high negative value of the residual anomaly with an amplitude of above 0.2 mGal indicates a significant missing mass that is usually associated with the presence of sub-surface cavity. This may indicate a still-incomplete filling of old excavations or a presence of a new activity of subrosion [23].

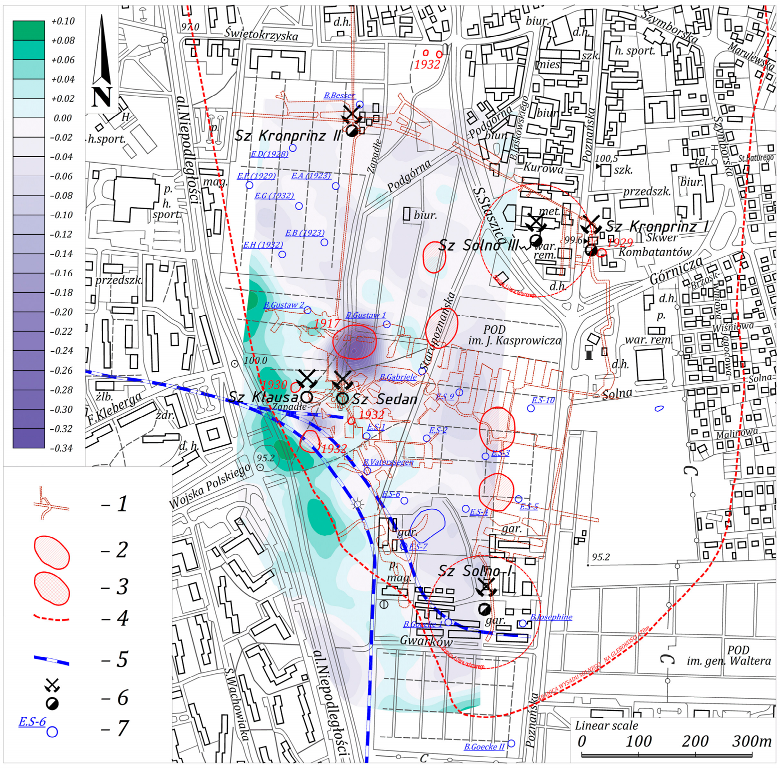

Figure 4. Distribution of residual gravity microanomalies (in milligals) in the area under study (the distribution after [23], modified). The legend presents the signatures used on the map and their numerical designations; their meaning is as follows: 1—boundary of the area under study; 2—sinkholes existed before 1861 according to [18]; 3—sinkholes occurred after 1861 according to [18]; 4—boundary of the salt dome at the depth of 470 m; 5—historic, currently non-existent railway lines; 6—abandoned mine shafts; 7—boreholes.

However, the occurrence of anomalous zones associated with old sinkholes was not observed, which indicates that they were effectively filled with saline and that karst phenomena had not developed within them. Nevertheless, as was mentioned, the outline of the anomaly confirmed the reliability of the information about the existence of flooded underground workings from the beginning of the twentieth century that which are outlined on mining maps from that period of time (Figure 1).

While anomalous zones in the area under study were identified thanks to the use of gravimetric measurements, in the absence of geodetic measurements, it was impossible to characterize the displacements of the ground surface there due to the absence of geodetic measurements. In another part of the town, however, a very good understanding of such characteristics was obtained. Shortly after the closing down of the "Solno" mine and after the liquidation of the Inowrocław mining plant (a term defined by the country's mining laws and dealing with concessions and granted rights for mining operations) the monitoring of ground surface deformation was halted. In the years 2002–2005 and in 2018, the authors, within a research study were carrying out measurements of the network of benchmarks located in Inowrocław using the precise leveling method. This network of the benchmarks was made using reference points located outside the former mining area of the "Solno" mine [21,22,26]. Areas of the vertical displacements of negative values were identified and despite the fact that they can be still observed, it was determined that they are vanishing. Recently the dominant trend has been noted of a decrease in ground subsidence and a clear increase in uplifts (in terms of their value and range of occurrence). Uplifts occur in the central and north-eastern parts of the dome [26].

The maximum annual changes for uplifts (positive values of vertical displacements) and subsidence (negative values of vertical displacements) in recent years are about 2 mm/year. It should be noted here that these values refer to changes recorded for benchmarks that are mounted on walls of large-volume buildings and for which the characteristics of height change are different than for those mounted in the ground. The characteristics of the vertical displacements in the town area have been widely discussed in [26].

As has been mentioned before, the shortcoming of geodetic works accounts for the lack of recognition of displacements in the western part of the area, an area which has been particularly affected by the occurrence of sinkholes. Hence, the authors came up with the concept of an indirect method for determining displacements, which is described below and which is a variant of the method they have called the Elevation Difference Method.

5. The Elevation Difference Method

While a significant part of the town area has been examined in terms of geohazards (resulting from old mining activities or geological phenomena and processes) via combined geophysical and geodetic methods, for the area in the western part of the town where the town's development was stopped 100 years ago, there has been virtually no knowledge of ground surface displacements for decades. This is due to the lack of observation points. The old ground benchmarks were destroyed years ago, which is typical for urban green space. Due to the lack of buildings in the area, it was not possible to mount wall benchmarks, which usually have a long durability (the oldest wall benchmarks in the town are over 120 years old and no ground benchmarks were saved).

The expected causes of these displacements could be the natural uplift of the salt dome (well recognized in the other part of the town), the effects of hydrological processes (suffosion, karst phenomena), post-mining effects (space enlarging of old excavations resulting for its leaching of their walls with unsaturated brine, etc.). As already mentioned, the location of sinkholes marked on old mining maps has not been confirmed by gravimetric measurements (unlike in other parts of the town), but it was possible to ascertain the gravitational effect of old mining excavations from the beginning of the twentieth century.

While there are no geodetic measurements that provide us directly with information on displacements, data of another type are available. They are records of the heights of topographical pickets included in old master maps of the town. The reason for their occurrence in land information systems was because of cartographic regulations regarding master map requirements [33]. Special geodetic instructions, and then ministerial ordinances, ensured detailed regulation of the rather high density of establishing such non-embedded control points, for which the height was determined, and thus were able to help to determine the characteristics of the relief.

Figure 5 shows a part of a section of the master map representing the analyzed area in the year 1978 (digitally remastered). This cartographic projection of the north-eastern part of the area analyzed here at that moment in time includes archival data, amongst which are the height of pickets. They are presented with an accuracy of 0.1 m and in some cases even up to 0.01 m. On the basis of master maps from 1978, topographic pickets were digitized, and in this way, information on 1589 points (height pickets) was obtained, which made it possible to assess the Digital Elevation Model (DEM) for the state of 1978. The same was also possible for the year 1998, but height pickets were entered in this case for geodetic and cartographic resources of the Inowrocław district. The latest data on the distribution of topographic heights for the area come from satellite measurements, which are made public and are given in the Kronstadt elevation system (the formal name of this datum is PL-KRON86-NH). This datum is no longer valid; it was replaced by the PL-EVRF2007-NH just as PL-KRON86-NH had replaced "Kronsztad 60" before it. In the case of the Kronstadt60, heights were expressed up to the 1980s. The average differences between these systems in Poland range from 2 to 8.5 cm [33]. This value is clearly lower than the accuracy of the topographic picket heights shown on the 1978 map. Nevertheless, research on height changes should take this fact into account.

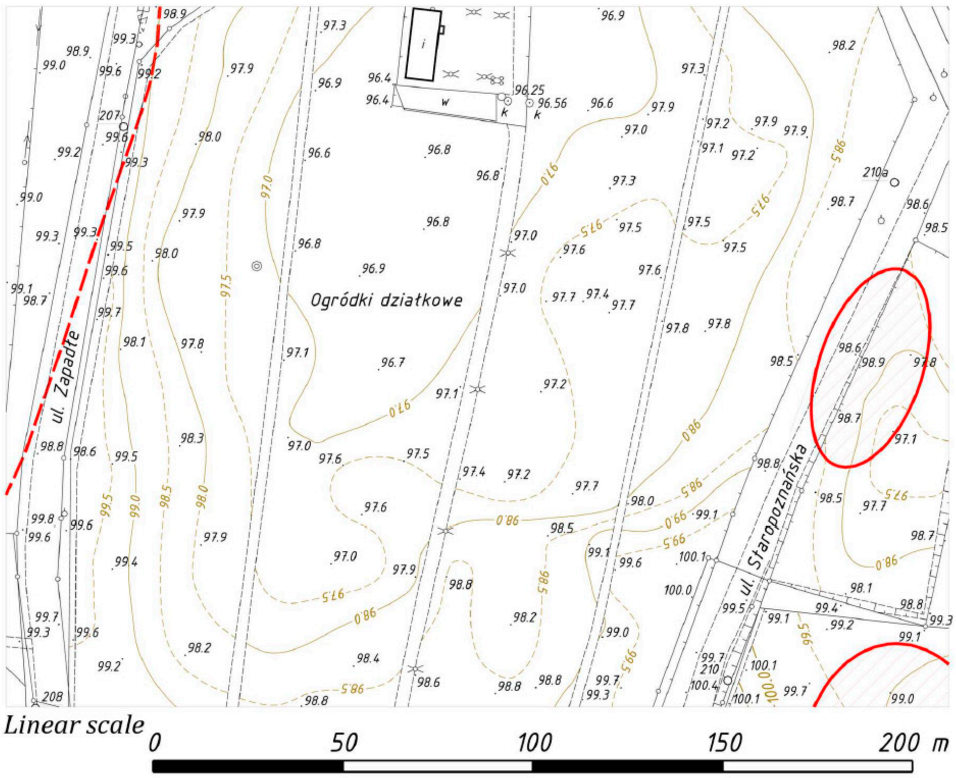

Figure 5. A fragment of a master map representing the northern part of the area under study for the state of 1978. There are topographical pickets, boundary of old drill mining (dashed red line) and localizations of old sinkholes (red continuous line).

It should be noted here that LIDAR (Light Detection and Ranging) measurement data from airborne laser scanning ALS (Airborne Laser Scanning) represent the terrain surface in the form of a cloud of measurement points with determined XYZ coordinates. The files are saved in the LAS format and, in addition to the coordinates of the points, contain information about the class of a given point and the intensity of the signal reflection, among other information. In Poland, the National Geodetic and Cartographic Resources comprise data for a Digital Terrain Model (DTM) based on aerial images, airborne laser scanning and topographic maps. All elevation data are created in the PUWG1992 coordinate system, and the heights of points relate to the Normal Height "Kronsztadt 86". Data for the area of Poland are available as part of the geoportal service: https://mapy.geoportal.gov.pl/imap/Imgp_2.html (accessed on 28 March 2023). There, you can view DTM using various services. Due to its high accuracy, this measurement technique has been widely used in displacement measurements for various purposes [34–36].

Generally, there are two basic types of DTM, which are based on different geometric structures, i.e., GRID—a model in the form of a regular grid of squares, and TIN—a model in the form of an irregular grid of triangles. In Poland, the basic numerical terrain model is a model in a 1 m $\times$ 1 m grid, which is systematically updated on the basis of Airborne Laser Scanning (ALS), but also—for urban areas—on the basis of stereoscopic measurements as part of the production of an orthophotomap with pixels of 10 cm or smaller. DTM is also developed in a 5 m $\times$ 5 m grid based on stereoscopic measurements in the production of an orthophotomap with a pixel of 25 cm. This gives 1,000,000 points for 1 km^2 of DTM in a 1 $\times$ 1 m grid. The area of the study was almost this size. Additionally, the high-resolution DTM was collected from the National Geodetic and Cartographic Resources obtained via airborne laser scanning (ALS) in 2018.

The basic assessment tool used in the analysis was a vertical displacement, the accuracy of which was determined by the errors in height measurement in individual years of a given time interval. Denoting the vertical displacement of the i-th point for the exemplary time interval 1978–2018 as:

$$\Delta H_i = H_i^{2018} - H_i^{1978} \tag{1}$$

the mean errors of the vertical displacement of the i-th point in this time interval were determined from the relationship:

$$m_{\Delta Hi} = \pm\sqrt{m_{Hi1978}^2 + m_{Hi2018}^2} \tag{2}$$

The accuracy of determining the heights of the topographical pickets in territorial mapping from the 1970s and 1990s was determined by allowing for an average error of 0.10 m for m_{H1978} and m_{H1998} (using surveying measurements), for LIDAR data using: m_{H2018} = $\pm$0.15 m, the error of displacement amounted to: $m_{\Delta H(1978-1998)}$ = $\pm$0.141 m and $m_{\Delta H(1998-2018)}$ = $\pm$0.180 m, and it is the same for $m_{\Delta H(1978-2018)}$.

6. Discussion

In accordance with the discussed approach (the Elevation Difference Method), the different morphologies of the terrain surface from the analyzed years were compared. The only information about the morphologies from the past is the data (topographic pickets) recorded on the master maps (which had to be produced due to the regulations for territorial mapping). Considering the large number of pickets, it was possible to develop a reliable model of the terrain surface. Based on the obtained points and using the Surfer v.23 software (Golden Software Inc., Golden, CO, USA), interpolation grids with a mesh size of 5 $\times$ 5 m were calculated using kriging, and as a result, terrain surface models were determined for the individual years. They took the form of regular grids, with geometries consistent with those of the LIDAR data (2018). The interpolation error was computed as: error = interpolated value $-$ observed value. The obtained interpolation error is characterized by small values of single millimeters, so these values are two orders of magnitude smaller than the error of the determined height changes and do not affect the analysis result.

Thanks to this approach, we were able to determine the changes in the terrain surface for the time intervals 1978–1998, 1998–2018, and for the long interval of the period of time from 1978 to 2018. Figures 6 and 7 show spatial distributions, respectively, for the longer (with more significant changes) and the shorter time intervals. Extremely high values of height changes on the western border of the area under study, in its northern and southwestern parts, are the result of the reconstruction of communication routes.

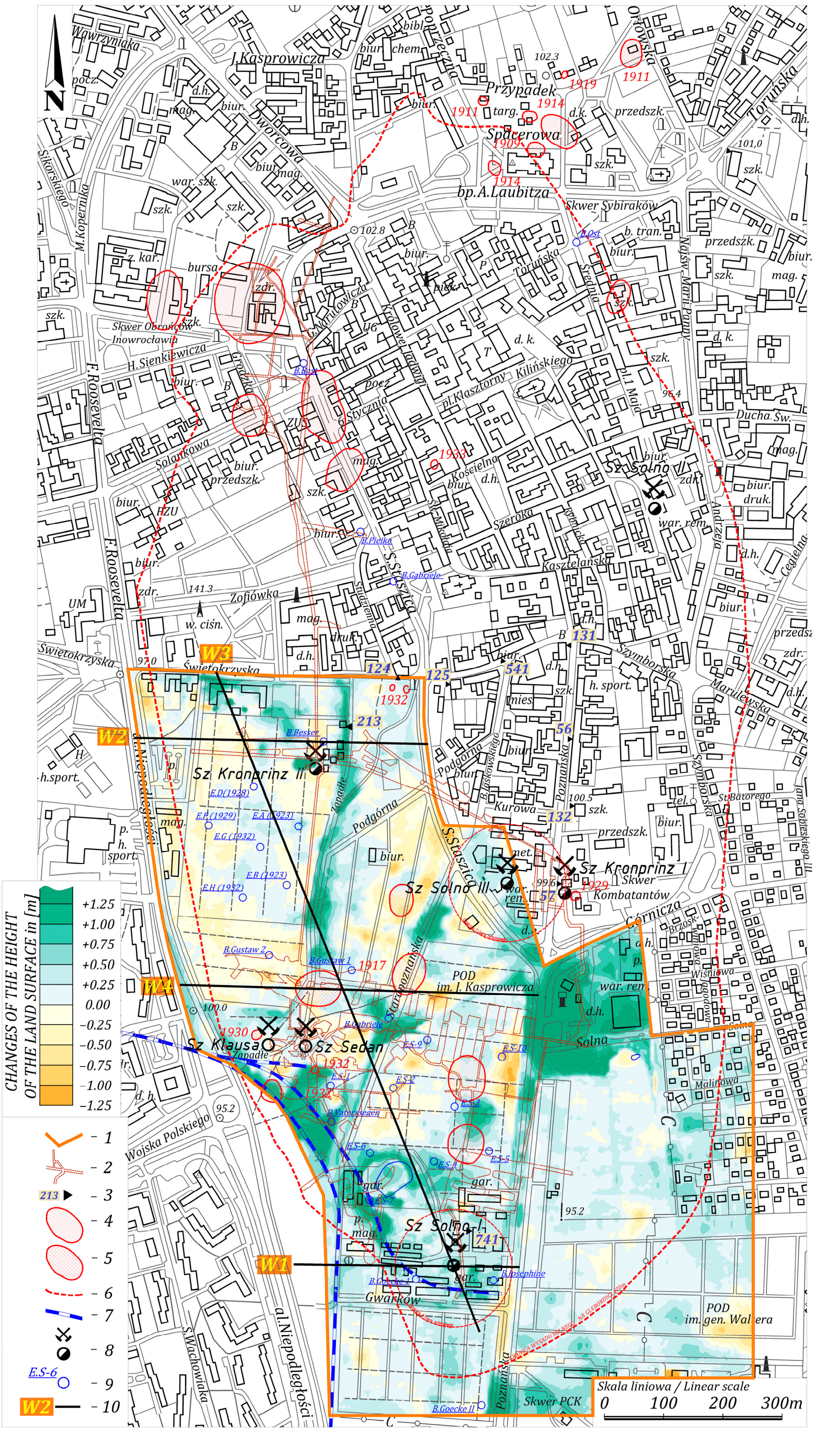

Figure 6. The map of the height changes in the time interval of 1978–2018 and locations of abandoned mine workings in the area. The legend presents the signatures used on the map and their numerical designations/ Their meaning is as follows: 1—boundary of the area under study; 2—workings of the shallow mines from the beginning of the twentieth century; 3—benchmarks of leveling measurements; 4—sinkholes that existed before 1861, according to [18]; 5—sinkholes that occurred after 1861, according to [18]; 6—boundary of the salt dome at the depth of 470 m; 7—historic, currently non-existent railway lines; 8—abandoned mine shafts; 9—boreholes; 10 —profile lines.

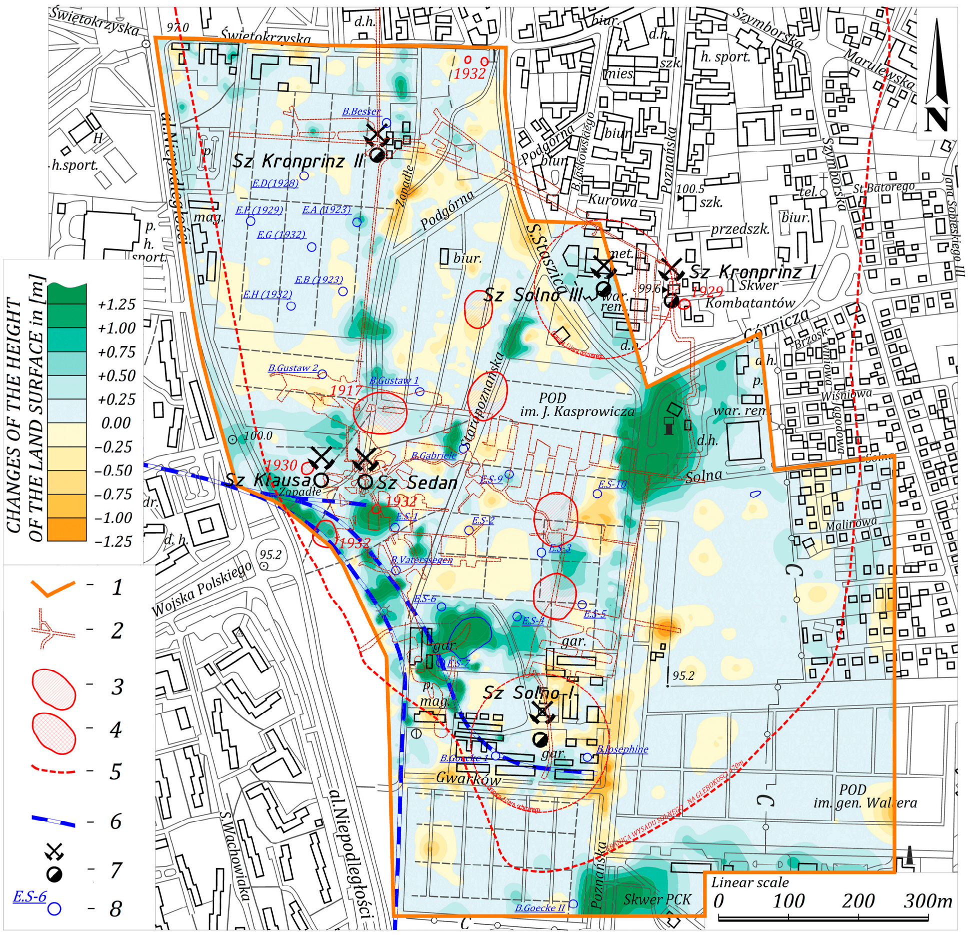

Figure 7. The map of the height changes in the time interval of 1978–1998 and locations of abandoned mine workings in the area. The legend presents the signatures used on the map and their numerical designations. Their meaning is as follows: 1—boundary of the area under study; 2—workings of the shallow mines from the beginning of the twentieth century; 3—sinkholes that existed before 1861, according to [18]; 4—sinkholes that occurred after 1861, according to [18]; 5—boundary of the salt dome at the depth of 470 m; 6—historic, currently non-existent railway lines; 7—abandoned mine shafts; 8—boreholes.

The statistical analysis has provided valuable insights into the characteristics of the height change distributions. For a short time interval (1978–1998), and at a level of height change above the margin of error value (>|0.141| m), 52.0% of the set of all points were found to show height changes above the margin of error value (10.6% of them demonstrated subsidence, and 41.4% of them demonstrated uplift). However, for the longer time interval (1978–2018), and at a level of the changes above the margin of error value (>|0.180| m), 68.9% of the set of all points showed height changes above the margin of error value (13.9% demonstrated subsidence, and 55% demonstrated uplift).

Similar results were obtained using a more rigorous approach in the statistical analysis that examined changes in the topographic picket heights since 1978 (in these cases using just the measurement points, not points produced from the interpolation algorithm). Therefore, for the points with the coordinates of these pickets (1589), their heights were estimated on subsequent DTM models, and as a result, height changes were determined for the points. These points could be considered as the corresponding points of the topographic pickets (projections of these points) on the other terrain surfaces, working from results gained from the base (reference) terrain surface of 1978 on the other terrain surfaces. These were projections including that which was determined from LIDAR data (2018). The distributions outlined as histogram plots presented in Figure 8 clearly demonstrated that the number of the changes in which the values are above the error value increased during the longer time interval and the changes in positive values became more frequent. The same conclusion can be drawn from an examination of the height change maps (Figure 6). As shown in the figure, only minor zones in the area under study showed negative height changes (subsidence) at a significant value.

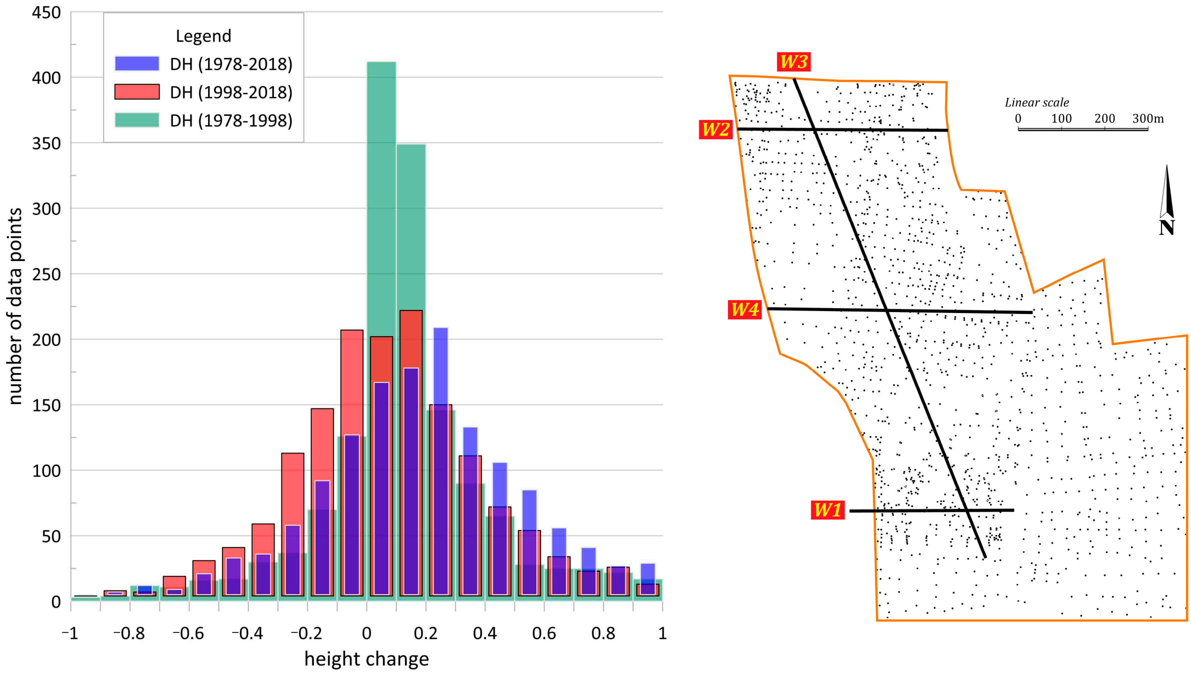

Figure 8. Histogram of height changes of points (in meters) for the assumed time intervals and the location of reference points (from 1978) on the right.

Zones of the height changes which were determined for the 1978–2018 time interval are clearly noticeable: the southern part of the area represents uplifts, whereas in the northern area, a large variability was recorded. Both positive (uplift) and negative (subsidence) height changes can also be distinguished. The zone of uplifts in the northern part of the area under study is placed in its central part, while on the western and eastern sides, subsidence has been found. While the areal distribution of the height changes seems complicated, the profile line distributions are more understandable, especially if the distributions of these changes are related to the profile of the salt roof surface.

Four profile lines that run through characteristic zones in the area under study were selected for analysis. Three of them (W1, W2, W4 profiles) pass latitudinally through the area and the other one of them passes it nearly longitudinally. The W4 could be considered an essential profile line because of the fact that it runs just above the workings of shallow mining and their catastrophic flooding and collapse in 1907. The profile lines were also as follows in light of the means of the characteristics of the elevation of the salt layer of the dome, as well as the characteristics of the terrain surface in the years 1978, 1998, 2018:

- The W1 profile line runs over flooded workings in the area of the Solno 1 shaft, and this part of the area in recent decades was not significantly affected by mining, and all mining works were stopped there in the 1960s [18]. Furthermore, as in this part of the area, no sinkhole has been documented as having appeared, this zone can be defined as being non-hazardous from the point of view of this particular risk. As can be seen in the W1 profile, in the first period (1978–1998) the changes in height were relatively insignificant (Figure 9). Only in the central part of the profile were there uplifts on the edges and subsidence, which in the eastern part of the profile showed significant values, i.e., values twice as large as the error in determining the height change. The topographic profile reflects the morphology of the top of the salt rocks of the diapir, but a certain horizontal shift in the characteristics of the profiles is visible. The ten-meter relative heights of the roof surface of salt correspond to the one-meter differences in the terrain profile. As shown, the height changes which occurred in the first short period (1978–1998) mostly amounted to negative values, although at a value close to zero, which made them not significant. In the next short period, the characteristics of the changes are more clearly defined and uplifts dominate, especially in the eastern part of the profile. Finally, in the longer time interval (1978–2018), only positive changes can be found, usually producing results well above the error value. In the middle of the profile, they increase as we move east and in the eastern part of the profile, they obtain significant values that oscillate around 1 m.

- The W2 profile line is located in the northern part of the research area and is in the vicinity of a part of the town that has been quite well examined in terms of ground surface movements (leveling, GNSS measurements). This is an area which is placed over the central part of the deposit, which has been showing uplifts for years, as has already been discussed intensively in this work [26]. The changes in the height of the terrain profile presented in the figure also show the dominance of uplifts, but changes with significant values also appear at the beginning of the profile and in the 300–400 m section (Figure 10). In turn, in the 100–200 m section of the profile, significant changes with negative values can be noticed. The distribution of topographic height changes is strongly related to the height distribution of the geological profile of the morphology of the salt rock roof. A certain discrepancy is visible: the elevated part of the topographic profile shows a local depression, which may be the result of underground erosion. This depression is not shown, however, in the geological profile.
- The W3 profile line is a line running longitudinally through zones of sinkholes which occurred in the past and whose locations are associated with the activity of underground waters flowing in underground valleys and in tunnels in the gypsum cap at the top of the dome, and flowing in a direction from north to south (see the section "Geoenvironmental setting"). The distribution of the changes in topographic heights shows a strong correlation with the height distribution of the geological profile, but only within the 500–1100 m section of the profile (Figure 11). Earlier, in the northern part of the profile, the mutual incompatibility of data distribution of the changes is visible. In this part, no height changes can be observed in each of the analyzed time intervals. For the 1978–2018 time interval, in the southern half of the profile line, negative changes in height are visible (on average about -0.5 m), and are visible over the area of shallow underground exploitation and sinkholes. In the final part of the profile, the changes in height are found to be positive (on average, about -0.5 m).
- In both periods (1978–1998 and 1998–2018) the changes are similar for most of the W4 profile. In the western part of the profile, an increase in subsidence is visible as it moves eastwards. Where the profile line passes over the workings of the old, shallow exploitation, a cessation of height changes is visible (Figure 12). This profile line in the further part of the profile, immediately after passing over the above-mentioned workings, reappears and shows similarly high values of 0.5 m, but only for the second period. In the first period, the changes are slight. In the longer term (1978–2018), changes in elevation on the part of the profile above those mentioned are also positive, but they are small values. It can be assumed that the entire area of the deposit, with the exception of the flooded parts of the rock mass, is subject to erosion, which is manifested by subsidence on the surface. While the profile shows a residual gravity anomaly as an effect after the previously mentioned 1907 disaster, no changes in height correspond to the gravitational effect (Figure 13).

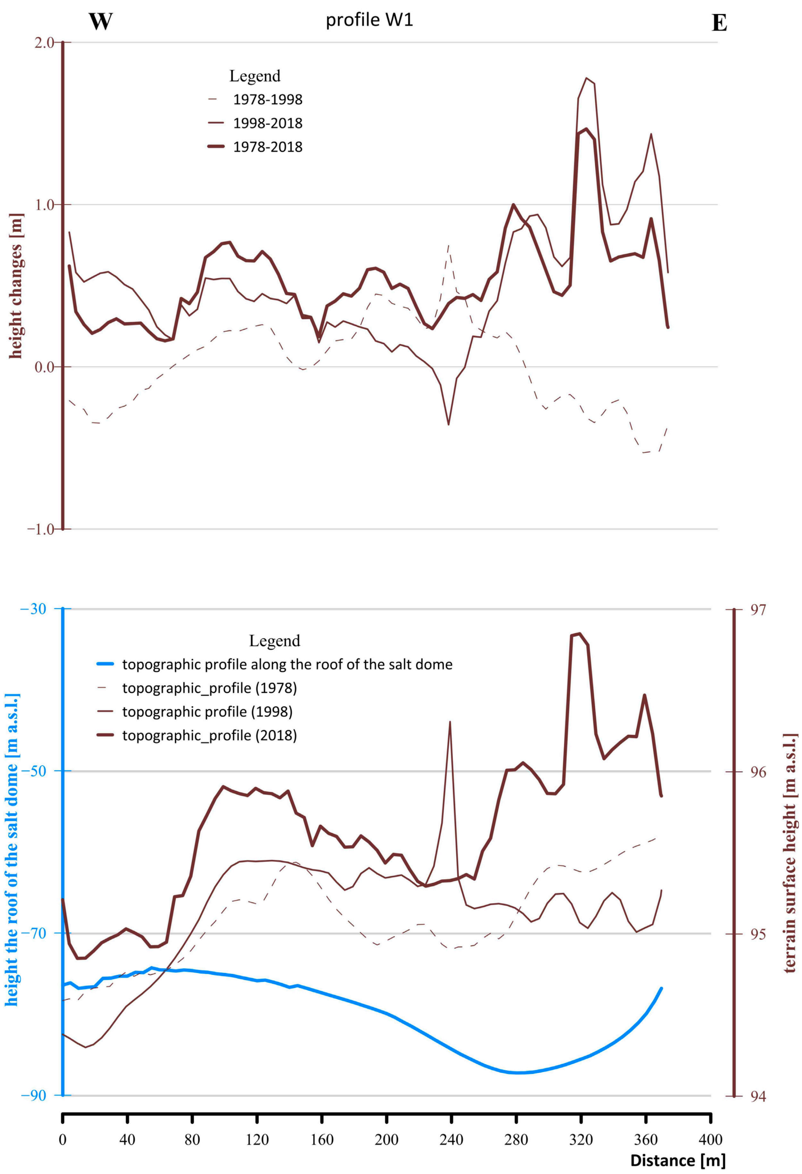

Figure 9. The topographical profiles of the ground surface in the particular years with the profile line of the top surface of the salt deposit. The plot at the top shows the height changes along the W1 profile line in the analyzed time intervals.

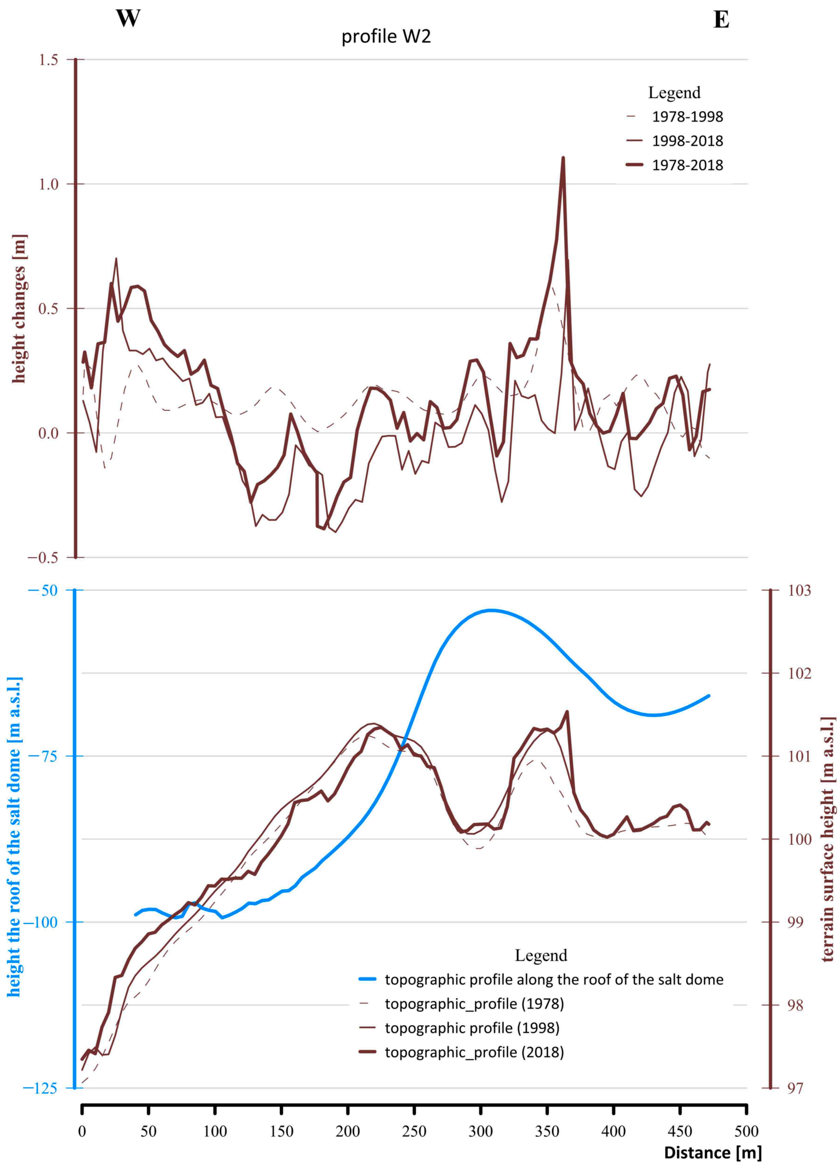

Figure 10. The topographical profiles of the ground surface in the particular years with the profile line of the top surface of the salt deposit. The plot at the top shows the height changes along the W2 profile line in the analyzed time intervals.

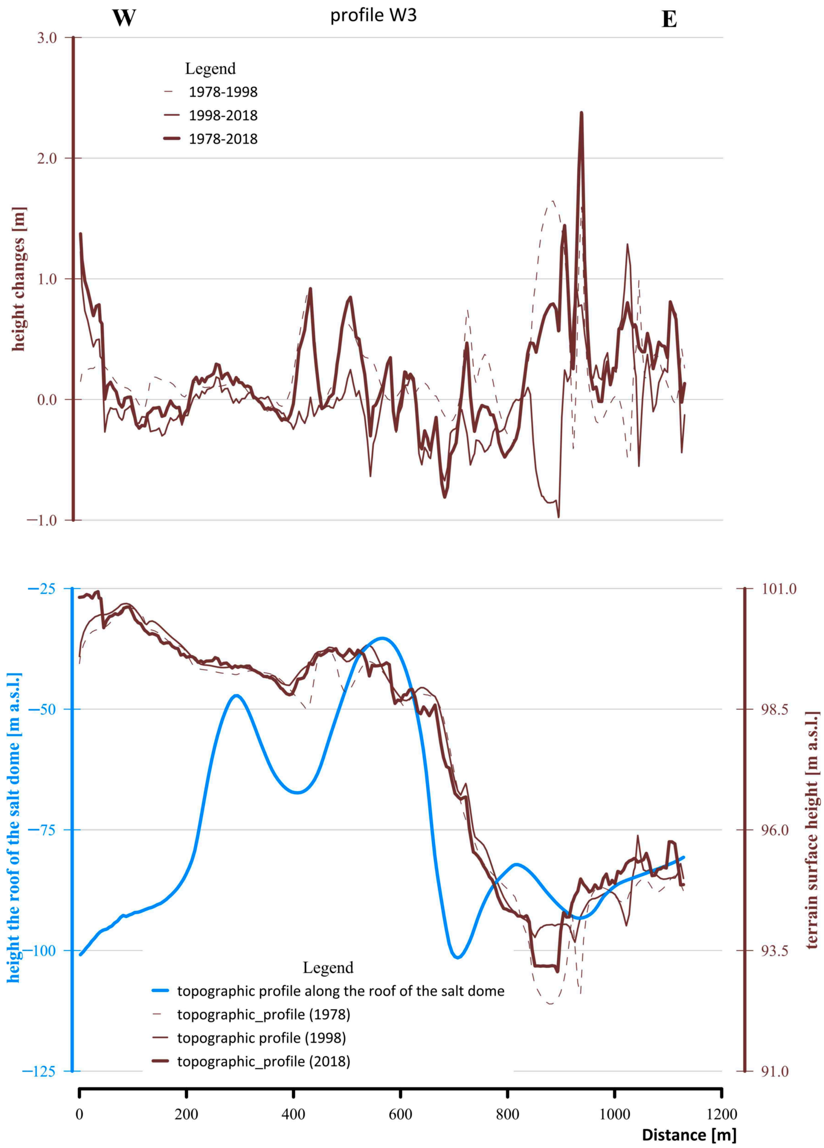

Figure 11. The topographical profiles of the ground surface in the particular years with the profile line of the top surface of the salt deposit. The plot at the top shows the height changes along the W3 profile line in the analyzed time intervals.

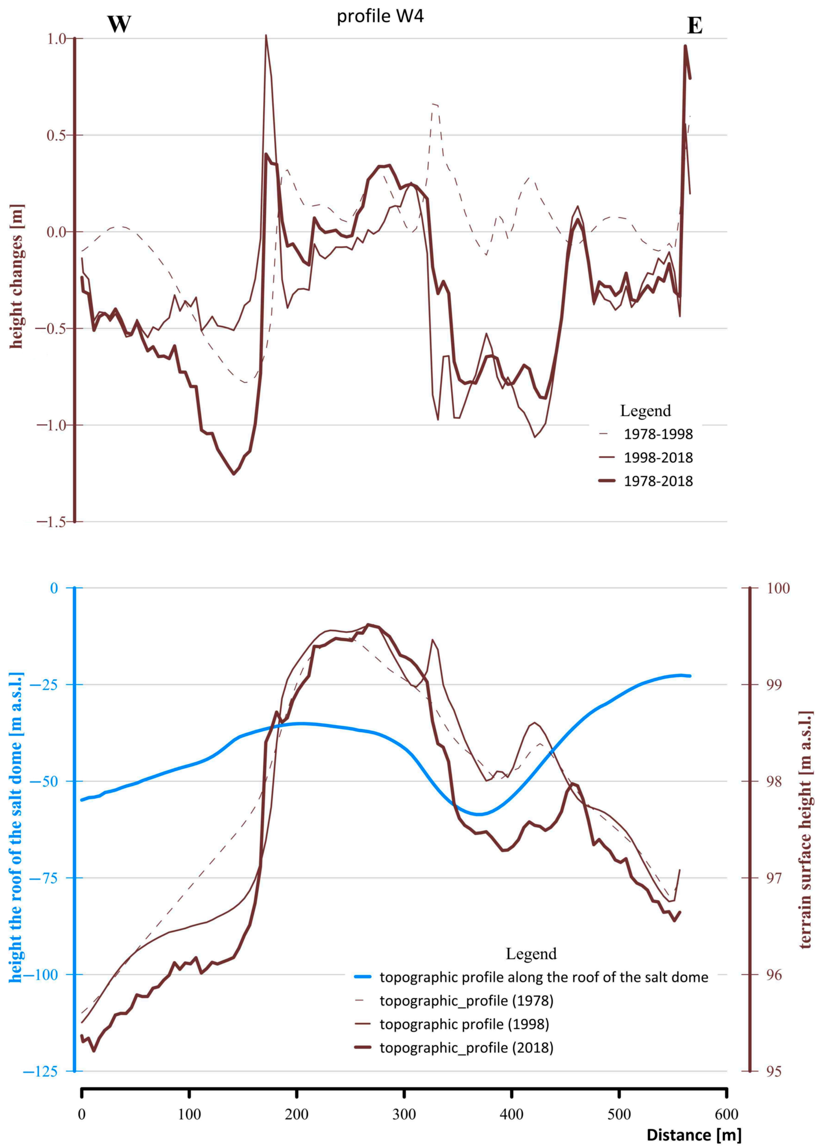

Figure 12. The topographical profiles of the ground surface in the particular years with the profile line of the top surface of the salt deposit. The plot at the top shows the height changes along the W4 profile line in the analyzed time intervals.

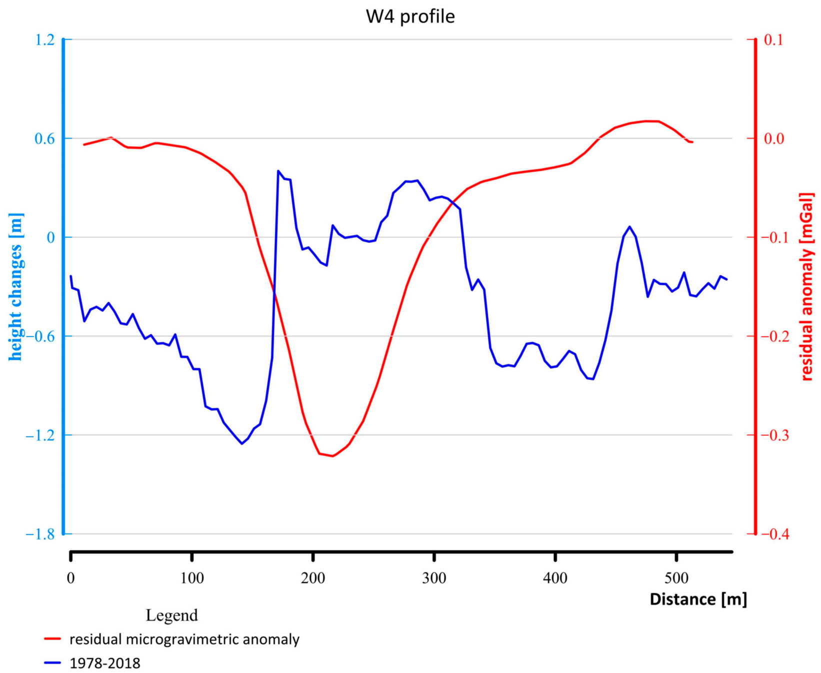

Figure 13. The distribution of residual microgravity anomaly (red line) and height changes between 1978 and 2018 along the W4 profile line (blue line).

7. Conclusions

The risks posed by sinkholes are becoming a particularly severe problem in urban areas and in spatial planning, where it is necessary to assess the suitability for development of areas at risk from sinkholes, or at a risk from a certain probability of the occurrence of sinkholes such as, for example, in the town of Inowrocław.

Geodetic and geophysical monitoring are then required, as is knowledge about the geological and hydrogeological background of the area. This combination of data provides knowledge about the conditions in which sinkholes are formed, and also the process of their formation, and may enable the assessment of the probability of their occurrence. The presented work highlights this problem and shows an example of geohazard monitoring.

In 2018, the authors received a commission from the town authorities of Inowrocław to assess the safety of the surface facilities for the town area with the aim of implementing a new division of the area of land in question into land development zones. The research carried out at that time allowed for the adoption of new solutions, which were less demanding in their terms related to the creation of new buildings.

The problem of assessing ground surface movements in this specific area of old sinkholes and old drilling and shallow underground mining has remained unsolved so far. To make this task harder, the area which is the subject of the analysis presented here is an area without geodetic points. Soon, after our investigation started, LIDAR data were made public, which made it possible to indirectly assess ground surface movements. However, these data had to be compared to the situation from years ago. Such previous data included information obtained in the years 1978 (when heights of topographical of 1589 points were determined) and 1998 (2842 points). The distribution of heights was analyzed—the distribution of height changes, in particular. The analysis was performed for areal distribution and for the distribution of profile lines. Characteristics of terrain surface profiles and their changes in the above-mentioned time intervals were analyzed in light of geological data (the topography of the salt roof surface) and gravimetric data. Amongst the many conclusions that could be derived from this research, the most significant are as follows:

1. The surface topography changes (small hills and small valleys) of the area largely follow the morphological characteristic of the salt layer at the top of the dome. Furthermore, the distribution of these morphological elements at the terrain surface indicates their mutual connection with the characteristic of the determined height changes: the most elevated part of the roof of the salt layer clearly corresponds to increases in elevation of the terrain surface and positive height changes (uplifts). In turn, the lowered part of this roof corresponds to decreases in elevation of the terrain surface and negative height changes (subsidence). This observation leads to an understanding of the mechanism of the geological processes which control the ground surface topography and ground surface displacement.
2. Uplift is the dominant trend in the observed height changes in the period 1978–2018, and the average value of these changes is approximately 0.25 m. This value is higher than the error of the determined height change, and therefore should be considered significant. It was found that the annual changes determined on this basis amounted to approximately 6 mm/y. While the activity of the Inowrocław diapir is the only instance of such activity in the European lowlands to which scientific studies have been devoted, the presented work is the first in which LIDAR data were used to describe diapir movements in the area of European Zechstein salt formation.
3. The authors discussed the efficiency of the presented approach, which relies on the combined use of written data and remote sensing data for ground stability assessment. The authors found that in areas that were subject to shallow mining exploitation a hundred years ago and where sinkholes were documented on old maps, no negative changes in height were observed (except for a small zone in an area of the Gustaw 2 shaft). And this stability of the ground surface exists there despite the presence of gravity anomalies. The determined gravitational and topographic effect at the site of the old exploitation, in the light of the data on vertical displacements, should be treated as a "scar" in the structure in the near-surface part of the deposit, which has no—or only a negligible—influence on surface movements which have been caused by the uplift of the diapir in this part of the area.

The results of this research do not indicate any occurrence of subsidence in the short term in areas of old exploitation and old sinkholes. One of the possible reasons for subsidence could be associated with the development of flooded or buried caverns, which could produce potential threats to the ground surface. However, in the long term, due to the natural degradation processes of the roof part of the dome, such a threat should be taken into account, especially in certain places such as old production wells, shafts, and sinkholes.

The aim of this work was not to introduce new techniques and analyze their possibilities, but to apply them to a specific problem in a city with a rich history. An unintended result was the determination of diapiric movements caused by the Inowrocław salt dome, and the obtained results correspond to those previously discussed by the authors [26]. Therefore, this is another work documenting the movements of this diapir, which is thus far the only diapir in the European Zechstein salt formation with such documented tectonic activity. Moreover, this work can be considered the first to use the LIDAR technique for this issue and in this area. While examining height changes, the authors have found that their spatial and temporal distribution was complex, as the mechanism that controls the analyzed displacements is multifaceted and most likely not driven by a single cause. However, the analysis of long-term data allows us to capture the trend; although it is complex, it clearly indicates an increase in the size of the area subject to uplift in subsequent years.

The research results can be used as an example to conduct analogous analyses of vertical displacements of the ground surface using various types of DTM data. In the case under discussion, these results can be used by Inowrocław authorities as a substantive basis for an assessment of a new category of spatial development zones. Due to the ever-present possibilities of geohazards, we feel that our research will help the authorities conduct an assessment which takes into account the current state of the surface deformation.

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