sustainability

MDPI

Article

Evolution of Secondary Deformations Captured by Satellite Radar Interferometry: Case Study of an Abandoned Coal Basin in SW Poland

Jan Blachowski, Anna Kopeć, Wojciech Milczarek * and Karolina Owczarz

Faculty of Geoengineering, Mining and Geology, Wroclaw University of Science and Technology, Wybrzeze Wyspianskiego 27, 50-370, Wroclaw, Poland; jan.blachowski@pwr.edu.pl (J.B.); anna.kopec@pwr.edu.pl (A.K.); karolina.owczarz@pwr.edu.pl (K.O.)

* Correspondence: wojciech.milczarek@pwr.edu.pl; Tel.: +48-71-320-4862

Received: 13 December 2018; Accepted: 1 February 2019; Published: 8 February 2019

Abstract: The issue of monitoring surface motions in post-mining areas in Europe is important due to the fact that a significant number of post-mining areas lie in highly-urbanized and densely-populated regions. Examples can be found in: Belgium, the Czech Republic, France, Germany, the Netherlands, Spain, the United Kingdom, as well as the subject of this study, the Polish Walbrzych Hard Coal Basin. Studies of abandoned coal fields show that surface deformations in post-mining areas occur even several dozen years after the end of underground coal extraction, posing a threat to new development of these areas. In the case of the Walbrzych area, fragmentary, geodetic measurements indicate activity of the surface in the post-mining period (from 1995 onward). In this work, we aimed at determining the evolution of surface deformations in time during the first 15 years after the end of mining, i.e., the 1995–2010 period using ERS 1/2 and Envisat satellite radar data. Satellite radar data from European Space Agency missions are the only source of information on historical surface movements and provide spatial coverage of the entirety of the coal fields. In addition, we attempted to analyze the relationship of the ground deformations with hydrogeological changes and geological and mining data. Three distinct stages of ground movements were identified in the study. The ground motions (LOS (Line Of Sight)) determined with the PSInSAR (Persistent Scatterer Interferometry) method indicate uplift of the surface of up to +8 mm/a in the first period (until 2002). The extent and rate of this motion was congruent with the process of underground water table restoration in separate water basins associated with three neighboring coal fields. In the second period, after the stabilization of the underground water table, the surface remained active, as indicated by local subsidence (up to −5 mm/a) and uplift (up to +5 mm/a) zones. We hypothesize that this surface activity is the result of ground reaction disturbed by long-term shallow and deep mining. The third stage is characterized by gradual stabilization and decreasing deformations of the surface. The results accentuate the complexity of ground motion processes in post-mining areas, the advantages of the satellite radar technique for historical studies, and provide information for authorities responsible for new development of such areas, e.g., regarding potential flood zones caused by restoration of groundwater table in subsided areas.

Keywords: ground motion; secondary subsidence; abandoned coal mines; PSInSAR; ERS 1/2; Envisat; Walbrzych (Poland)

1. Introduction

Mining activity, especially underground mining operations, change the hydrogeological conditions of the environment surrounding the mine, sometimes drastically. Interference of mining in the surrounding rock mass results in a groundwater level depression as the water is pumped out to extract the mineral. In turn, the cessation of mining results in a gradual restoration of groundwater levels following the end of mine water drainage. This process can evolve in a controlled or uncontrolled way, depending on the hydrogeological conditions of the rock mass. The restoration of the ground water level sometimes causes localized flooding on the surface, as the ground may have subsided during the time of mining below the original level of the groundwater table. The saturation of rock mass during a rise in the ground water level has an effect on ground stability and is frequently responsible for surface uplift because of changes in the hydrostatic pressure in the rock mass. This process is superimposed on the effects of secondary (residual) subsidence following a delayed reaction of the rock mass, which also includes the destruction of underground workings, especially those located close to the surface. For these reasons and for the safety of infrastructure and people, it is necessary to observe ground movements during reconstruction of the groundwater table, as well as later on [1,2].

Satellite Radar Interferometry (InSAR) is now a well-established technique for monitoring ground surface movements and is capable of surveying large areas at a competitive cost and comparable precision when compared to other techniques (e.g., leveling and GNSS measurements). A significant advantage of InSAR is that satellite radar images are collected continually and allow looking back in time and analyzing historical ground movements. Various interferometric techniques have already been applied to study surface changes related to both active and inactive underground hard coal mining.

Notable applications of SAR interferometry in studies of secondary deformations in post-mining areas have been described by Raucoules et al. [3] and Cuenca et al. [1]. These examples show the scope of InSAR applications for mining-related ground movement studies that include the application of a variety of SAR sensors, different processing techniques, different mining sites, as well as the diverse goals of these studies. Within the scope of this paper, the following examples of InSAR applications in detecting secondary deformation on mining grounds were reviewed. The most important details from the literature review are presented in Table 1.

Table 1. Literature review in a tabular summary. ISBAS, Intermittent Small Baseline Subset.

Publication Date	Authors	Processing Technique	Data stack Interval	Location
1998	Perski Z. [4]	DInSAR	ERS-1/2: 1992–1995	Silesian coal mine, Poland
2001	Ge L. et al. [5]	DInSAR and GPS	ERS-2: 2001	coal mine, Australia
2004	Wegmuller U. et al. [6]	DInSAR	ERS-1/2: 1995–1997	coal mine, Ruhrgebiet, Germany
2008	Baek J. et al. [7]	SBAS	JERS-1: 1992–1998	coal mine in Gangwon, South Korea
2013	Samsonov S. et al. [2]	SBAS	ERS-1/2 and ENVISAT: 1995–2009	coal mine, French-German border
2013	Bateson L. et al. [8]	PSInSAR	ERS-1/2: 1995–2000, ENVISAT: 2002–2008	coal fields, NE England
2014	Abdikan S. et al. [9]	PSInSAR	ALOS-PALSAR: 2007–2010	coal mine in Zonguldak, Turkey
2017	Vervoort A. and Declercq P.Y. [10]	DInSAR	ERS-1/2: 1992–2000, ENVISAT: 2003–2010	coal mine in Houthalen, Belgium
2017	Gee D. et al. [11]	ISBAS	ERS-1/2: 1995-1999 ENVISAT: 2002–2008, Sentinel-1: 2015–2016	coal fields, NE England

Perski [4] submitted his study to the area of the Upper Silesian Basin in Poland, where hard coal is mined. There is subsidence in this area, which is a threat to people and urban infrastructure. ERS satellite images from two years, 1992 and 1995, were used for the research. The generated interferograms based on the InSAR method identified ground subsidence in the range from 30–120 mm. Ge et al. [5] took care of monitoring the subsidence of land due to hard coal mining in Australia. For this purpose, the InSAR technique and GPS technique have been combined, because they are not very costly compared to other techniques. The use of GPS technology reduces errors in results obtained with the DInSAR method. The article presents technical details regarding radar reflectors and GPS receivers. Wegmuller et al. [6] focused on determining the surface deformation caused by underground coal mining of the German Ruhrgebiet in Germany. During the study, ERS-1/2 satellite imagery for the period from 1995–1997 was used. The DInSAR method was used in the processing, and the calculated displacements were a maximum of 60 mm.

Another example covers a study of mining subsidence in the Gangwon coal mining area in South Korea, where operations were carried out until 2003. With this aim, 23 satellite images from the JERS-1 satellite for the period 1992–1998 and the Small BAseline Subset (SBAS) technique were used to obtain detailed information of the course of subsidence. Ground deformations of up to 22 cm were confirmed [7]. In the subsequent study [8], coal fields in NE England were investigated. Datasets from ERS for the 1995–2000 period and Envisat for the 2002–2008 period were used for PSInSAR processing. Subsidence was determined in the southern part of the study area, and elevation was detected in the northern part. Ground movements from −7.5–+7.5 mm/y were attributed to changes in groundwater levels. Samsonov et al. [2] used SAR ERS-1/2 and Envisat images acquired between 1995 and 2009 from one ascending and one descending track for time series analysis of former coal mine on the French-German border. They detected a temporal variability of surface movements, in particular reversal from subsidence to uplift. The authors determined that deformation rate changes are mainly caused by water level variations in the former mines. The paper by Abdijan et al. [9] describes the results of a study in the coal mining area of Zonguldak in Turkey. Their results of processing ALOS-PALSAR data for the 2007–2010 period indicated subsidence rates between 30 and 40 mm/y for individual coalfields. A max. subsidence of −44 mm/a showed a correlation with the volume of coal produced.

The next case concerns former coal mine in Houthalen (Belgium) [10]. The authors, using ERS 1/2 and Envisat data, obtained a picture of ground movements during the 18 years following the end of mining operation there. The average ground motion was −5.5 mm/a within a zone of 2 km^2 for the first 8–9 year period and +8.6 mm/a in the last seven years of observation.

Finally, Gee et al. [11] followed their earlier investigations on abandoned coal fields in the United Kingdom (NE England) using the Intermittent Small Baseline Subset (ISBAS) DInSAR (Differential InSAR) technique on ERS 1/2, ENVISAT, and Sentinel-1 SAR images. They observed uplift of the ground that was attributed to increases in pore pressure in the rock mass following the cessation of groundwater pumping after closure of the mine. They also identified regional differences in the rate of uplift caused by local geological settings (faults).

These examples prove that a range of sources of satellite radar images is now available and that numerous processing techniques have been developed and successfully applied to study short- and long-term surface movements in areas of ceased underground mining activity.

Our approach uniquely focuses on long-term (1995–2010) analysis of ground movements of an enclosed coal mining basin in final stages and after the end of mining. To obtain a complete picture, the study was based on multiple SAR sources, i.e., ERS 1/2, Envisat from ESA, as well as information on ground water level change, geology, and mining. The research concerns the Walbrzych Coal Basin in SW Poland. This site is unique in terms of geological composition and hydrogeological conditions and was closed down within the last decade of the 20th Century. Particular attention in our study was paid to the relationship of ground movements and groundwater level rise after cessation of mine water drainage.

The study mainly contributes to the existing literature in the following ways:

1. The area of abandoned coal fields in SW Poland has not been subject to this sort of comprehensive and complex study before. As such, this paper will be a reference for future studies, and also for other areas.
2. The study area is unique as the flooding of its underground mines was an enclosed and mostly controlled process.
3. The correlation analyzes between changes in groundwater level and ground movements occurring in the literature [12,13]. However, they still require continuous study and the use of various measurement techniques.

This paper aims at the spatial and temporal analysis and determination of the relation between the rate and direction of ground movements and groundwater level changes in different, distinct parts of abandoned coal fields based on the results of piezometer readings and with the aid of spatial statistics functions.

2. Study Area

The Lower Silesia Coal Basin and its part, the Walbrzych Hard Coal Basin (WHCB) (Figure 1), are among many of the hard coal mining sites to be found across Europe. They were developed for a long time, and coal mining continued for several hundred years before being closed down in the 20th Century. The Walbrzych Hard Coal Basin is unique in the sense that the entire area is an enclosed structure in terms of geology and that all the mines were closed at roughly the same time in the 1990s. The coalfields were abandoned due to difficult mining conditions that made further operation unprofitable. In addition, the three underground mines that existed after World War II were flooded separately in a controlled process.

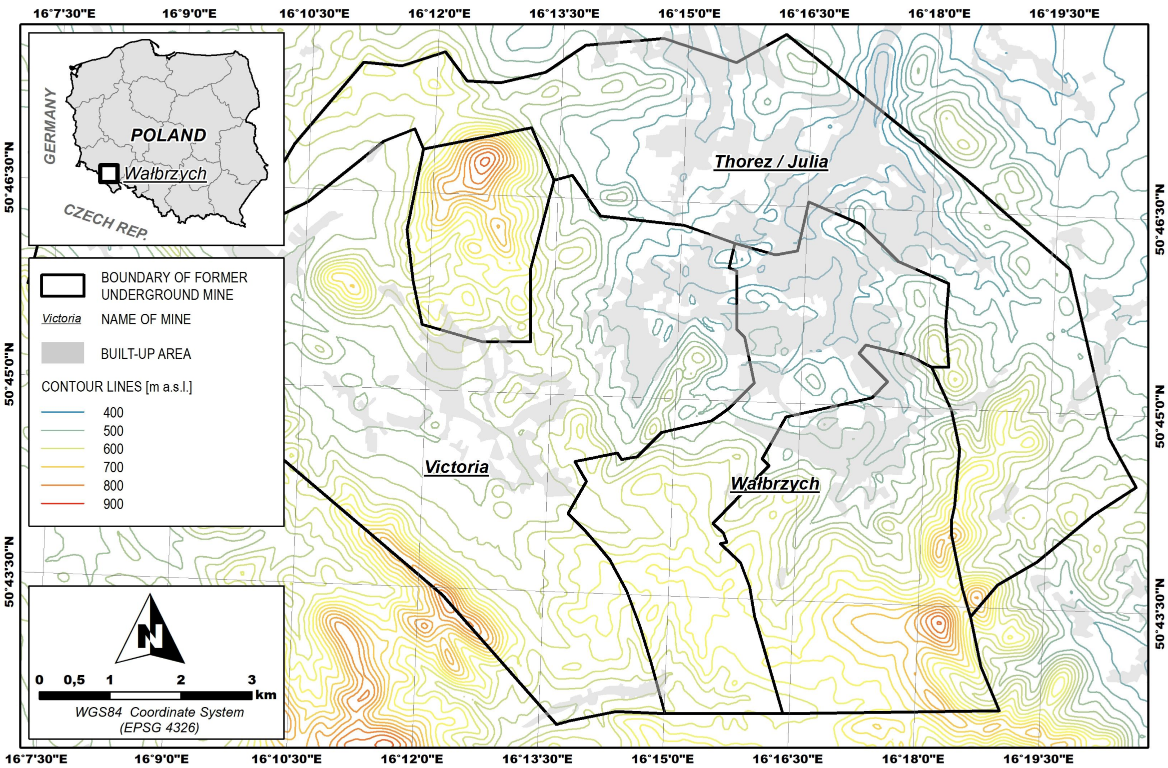

Figure 1. Location of the former mining area of Walbrzych Hard Coal Basin.

2.1. Geology

The area is associated with the largest unit of the Central Sudety Mountains called the Intra-Sudetic Basin. The basin is divided by a laccolith porphyry intrusion (Chelmiec intrusion) into two synclines named Gorecka and Sobiecin (Figure 2). In the Sobiecin syncline, located in the northern and eastern part of the area, the extent and direction ate parallel to the syncline W-E in the northern part to NE-SW in the southern part. The inclination of geological formations changes between 10 and 30 degrees, and in the vicinity of the porphyry intrusion, it reaches 70 degrees. In the Gorecka Syncline, the formations are lying asymmetrically with an inclination of between 10–40 degrees. The basin is filled with carbon, Permian, Triassic, and Cretaceous formations. The rocks are of sedimentary origin. Coal layers are associated with three of the four lithostratigraphic Pennsylvanian complexes: the Zacler, Bialy Kamien, and Walbrzych formations. Altogether, 80 coal seams have been identified, including 48 in the Zacler formations and 30 in the Walbrzych ones. The productive coal levels varied in thickness from less than 1 m to over 2 m. The stratal dips of the geological layers are towards the center of the two Sobiecin and Gorce basins, which are separated by the intruding Chelmiec mountain. The complicated geological structure is the result of intrusive and compressive tectonic activity. The throws of the main faults reach up to 300 m. In addition, there are numerous local faults with throws of several meters [14].

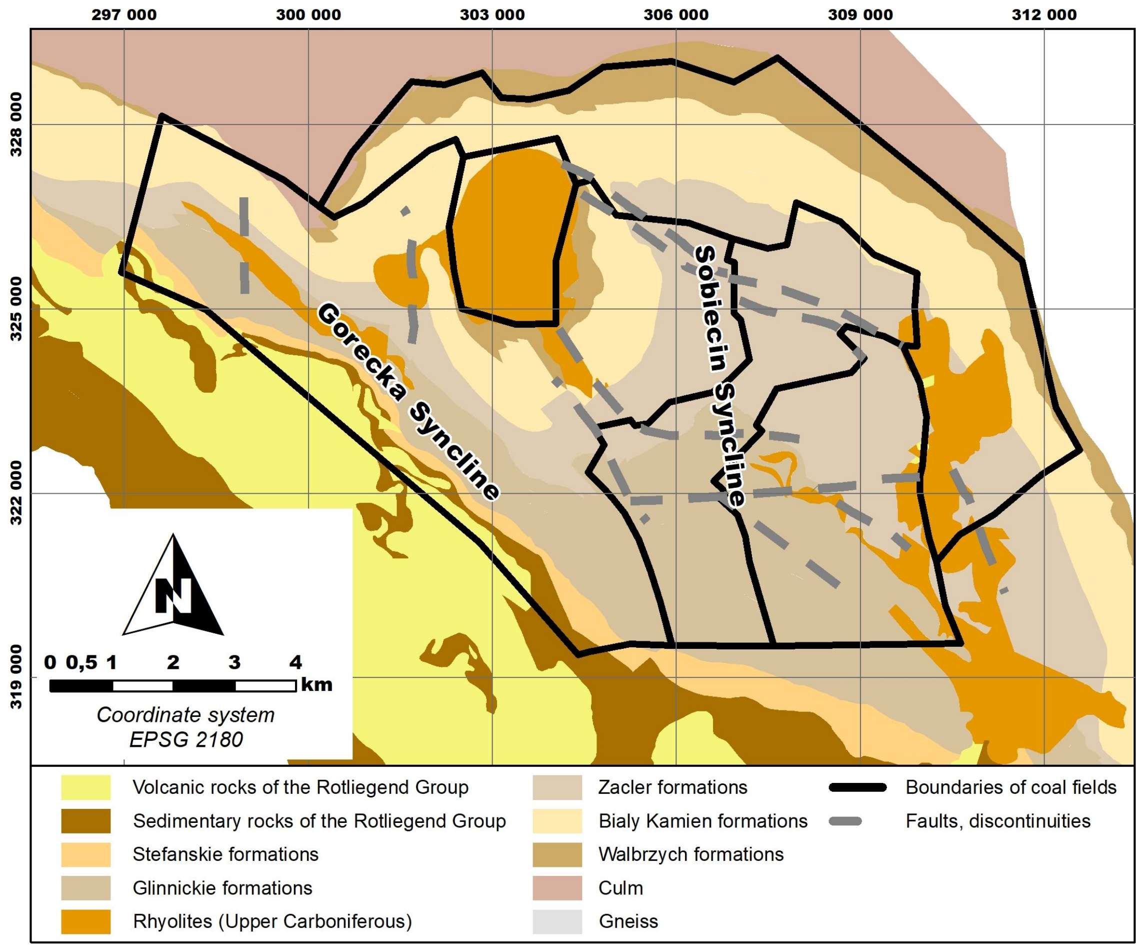

Figure 2. Geological structure of the Walbrzych Hard Coal Basin (WHCB) region with the locations of tectonic faults.

2.2. Mining

The first records of coal mining in the area date back to the 15th Century. In the second half of the 19th Century, railway connections were established, which caused a significant growth of coal production. After World War II, the area became the territory of Poland, and coal was mined in three separate mines named Thorez (Julia), Walbrzych, and Victoria. At the beginning, coal deposits close to the surface were extracted from the ground, and later on, shafts were introduced. The hilly ground also allowed for adits. From approximately the middle of the 19th Century, water draining shafts and pumps were introduced, and exploitation moved down to approximately −200 m a.s.l. With time, smaller mines were combined into larger units, and coal mining moved deeper. After WWII, the longwall mining system was used. Beginning in 1991, the process of mine closures started. Coal production gradually diminished and stopped completely on 30 September 1996. In the central, deepest part of the area, some anthracite production continued, but the operation ceased to exist on 30 September 1999, while the process of the liquidation of the underground workings could continue. The area of the coal fields covered approximately 94 km^2 [15].

2.3. Hydrogeology and the Process of Mine Flooding

There are two main underground water levels, Quaternary and Upper Carboniferous. The first one, due to its small thickness and being mainly limited to river basins, does not play a significant role in hydrogeological conditions. The basin is composed of rocks that have different permeability, sandstones, conglomerates, mudstones, shales, porphyries, and coal layers. Sandstones and conglomerates have the greatest thicknesses and determine the water circulation. The filtration coefficients of these rocks are not well known and will be very different (much smaller) in rocks unaffected by mining, as well as in areas of mining with voids left after exploitation and cracks resulting from roof collapse. Long-term coal mining and associated mine water drainage in the basin caused depression in the rocks of the basin. The depth of mine water drainage, and thus depression, is estimated at 1000 m below the surface of the ground. In the early 1990s, spontaneous mine flooding due to the end of mine water drainage occurred on most of the area. The basin was divided into separate underground water reservoirs (Figure 3), Barbara-Witold, Pokoj, Julia, and Victoria-Chrobry, by taking advantage of the natural hydrogeological conditions and with the construction of dams in the tunnels connecting exploited coal fields. The flooding started in November 1994 for the Witold-Barbara reservoir and in June 1995 for the Pokoj reservoir. The flooding of the Julia reservoir was controlled and executed in stages. It started in February 1994, and until June 1998, the water level was kept at −180 m a.s.l. After the end of anthracite mining in its central part, flooding was continued together with flooding of the Victoria-Chrobry reservoir. The extent of the underground water reservoirs and the approximate boundaries of the mined coal fields based on 19th and 20th Century mining maps is shown in Figure 3.

A network of piezometers was set up, usually in mine shafts, to observe the reconstruction of the underground water table. In the Barbara-Witold reservoir, the water level continued to rise steadily. The rate of the water table reconstruction (rapid rise by 70 m) was affected by a flood of 1997 in Southern Poland. In 2000, the water level in this reservoir stabilized. The reconstruction of the water level in the Pokoj reservoir was observed by using piezometers located in a mine shaft (Figure 4). Until mid-1996, when a hydraulic connection was established with the Julia reservoir, the water level rose continually up to 420 m a.s.l. This caused the water level in the Pokoj reservoir to oscillate depending on the amount of precipitation. It was then forecasted that the water level in this reservoir would rise again after the end of mine water drainage in the Julia and Victoria-Chrobry reservoirs [16].

Between December 1998 and February 1999, the mine water drainage in the last two reservoirs stopped, and they were flooded in an uncontrolled manner. It was then estimated that these reservoirs would be completely filled by 2003. Readings from piezometers indicated that temporarily-suspended local water tables developed in areas of limited hydraulic contact between mined zones and the untouched protective pillars.

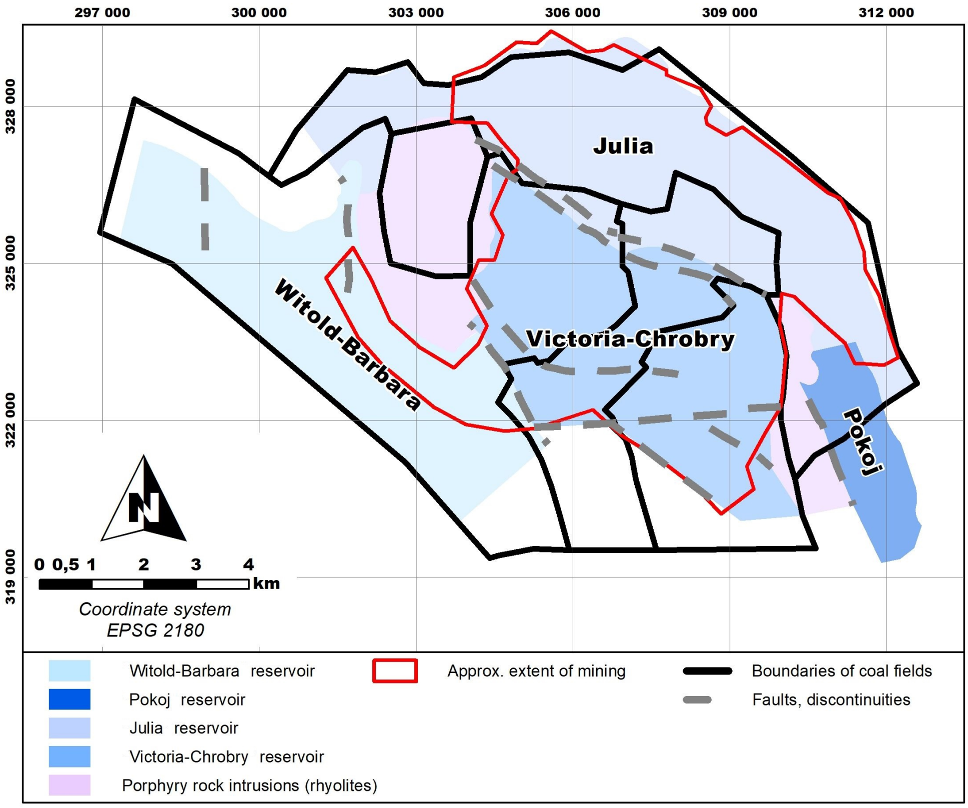

Figure 3. Borders of the WHCB mining areas with regard to the boundaries of underground water reservoirs. Local tectonic faults served as natural borders between the Julia and Victoria-Chrobry reservoirs and also between the Victoria-Chrobry and Witold-Barbara reservoirs.

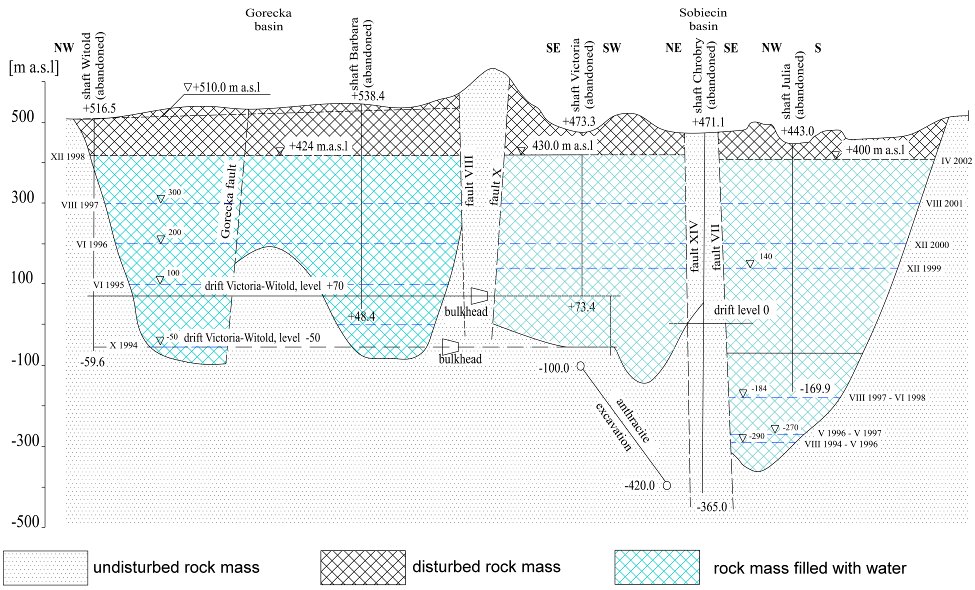

Figure 4. Schematic cross-section through the flooded underground reservoirs in the Walbrzych basin. The subsequent flooding stages of the water reservoirs are marked with horizontal dashed lines. Groundwater level measurement dates have been provided next to the blue dashed lines. After ref. [17].

3. Dataset and Methods

SAR images acquired from the European Space Agency served as the basic dataset for calculating ground motions in the Line Of Sight (LOS). The results presented in this paper cover the period from 1995–2010. The calculations were based on satellite radar data from ERS 1 and ERS 2 (C band, 56.6 mm, Path 308), as well as from Envisat (C band, 56.2 mm, Path 229) (Figure 5).

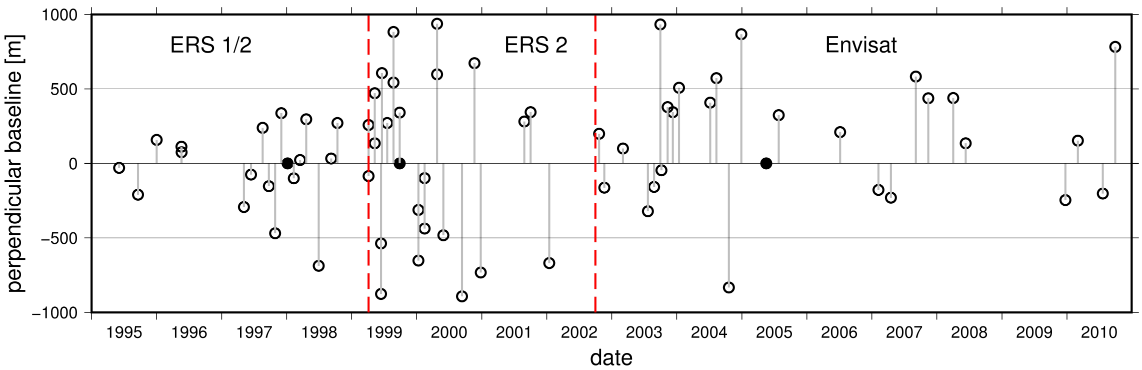

Figure 5. List of the SAR data used: ERS from 1995–2000, ERS from 1999–2003, and Envisat from 2002–2010. Black dots represent master images for each of the calculation sets. Vertical dashed lines represent the borders between the sets.

Time series of post-mining ground movements in Walbrzych were prepared with the use of the PSInSAR method [18]. The radar data were prepared by generating Single Look Complex (SLC) images from raw data and by calculating interferograms in DORIS (Delft Object-oriented Radar Interferometric Software) Ver. 4.02 [19]. PSInSAR calculations of the SAR data were performed in StaMPS (Stanford Method for Persistent Scatterers) [18]. Interferograms were unwrapped on the basis of the minimum cost flow algorithm in Snaphu [20]. Wave phase correction in relation to the ground surface was performed with the Shuttle Radar Topography Mission (SRTM) Version 1 (resolution: 30 m) [21]. Selection of a master image is of key importance in the first PSInSAR calculation step of SAR data.

Choosing a proper image depends on the time basis (days) between the potential image pair, on the perpendicular baseline (m), and on the difference in the Doppler centroid (Hz). A difference between successive pairs was calculated for each of the above parameters. The resulting master image should be selected in such a way that potential pairs of the master image and the nth slave image show the maximum limited differences between the above parameters. In the case of ERS 1/2, critical values for the perpendicular baseline and the difference in the Doppler centroid were 1100 m and 1380 Hz, respectively [22]. When selecting the master image from the ERS dataset, it was necessary to solve a problem resulting from the significant divergence of the perpendicular baseline (Figure 6) and from the high difference in the Doppler centroid values (which often exceed 2000 Hz). The analysis did not cover data from 1992, because SAR data from the beginning of 1993 until the end of 1994 were recorded in extremely different positions. The ERS 2 archive stores data recorded until 2010. However, despite many attempts to select the master image, it was impossible to obtain reliable results for the 2002–2010 period. For this reason, analysis for the period after 2002 was based on Envisat images, which have much more advantageous values of the perpendicular baseline and the difference in the Doppler centroid parameters for potential pairs.

For surface deformation studies in mining areas, the SBAS (Small Baseline Subset) method, which like the PSInSAR method, uses time series, has been also used. The methodology is based on selecting a single master (reference) image among the dataset. It then creates combinations of differential interferograms with the remaining images. The advantage of the SBAS method is that it alleviates the effects of signal decorrelation while increasing the number of consistent pixels in terms of time [23–25]. Notable examples of mining deformation studies with the SBAS method include [7,26–28].

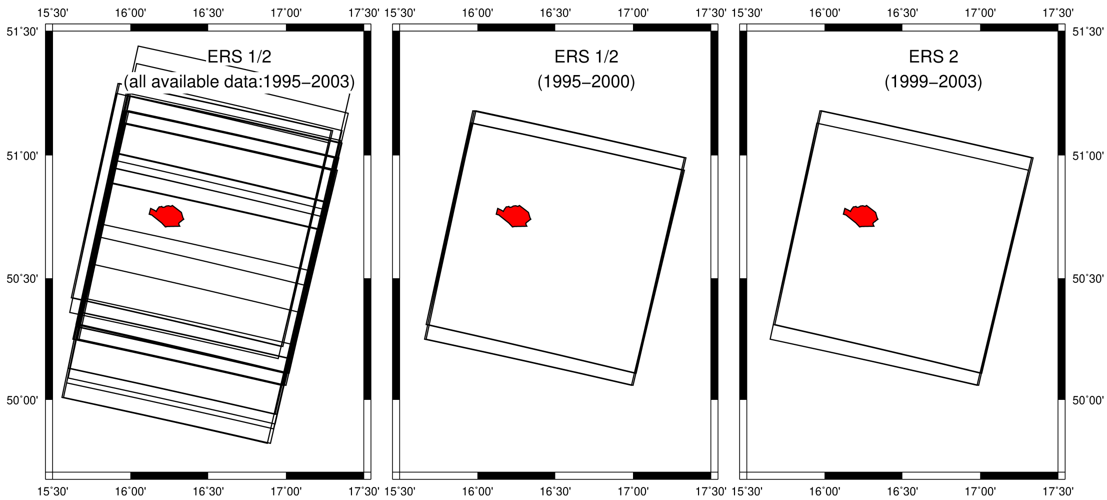

Figure 6. Selection of SAR data from ERS 1/2. The red polygon corresponds to the borders of the WHCB mining areas. The left-hand side of the figure shows the spatial distribution of SAR data from the analyzed Path 308, for the 1995–2010 period, a total of 147 images. It is interesting to observe the scale of image shift in the E-W direction, which is maximally 11 km. The middle part of the figure shows selected images for the 1995–2000 period and the right-hand side for the 1999–2002 period.

The time series PSInSAR method that was applied for detecting changes of the surface has limitations, just like other methods based on SAR data. The relative nature of the results, which were determined in relation to one master image (master date), is a significant limitation. Coherence, especially for this latitude (the Wałbrzych area), is another limitation of satellite interferometry. Low values of coherence significantly limit the ability to determine reliable results. Thus, the optimal solution in determining the movement of the surface is combining two, three, or even more measuring methods. A good example is the joint use of SAR and GNSS data [29–31] and in addition precise leveling [32]. However, it should be emphasized that in the case of the analyzed area, as well as the analyzed period (1995–2010), there are no available GNSS and precise leveling measurement data that could be used to investigate the phenomenon of surface movement. The available data for this area and period are the presented groundwater table level measurements.

4. Results

Numerous approaches can be used to analyze and visualize ground movements in coal mining fields: statistical analysis of PS points [33] or PS points congruent to reference units [34] and also interpolation [35] with the aim of indicating areas of statistically-significant values of upward or downward ground movements with the aid of GIS-based hot spot analysis. The latter was also included in our paper. The resulting values of mean annual ground movements for three calculation periods are shown in Figure 7. These maps were prepared with spline interpolation for optimized parameters of the function and verified with the cross-validation technique.

In the first period (1995–2000), two active areas are clearly visible on the surface. The first area was located within the borders of the Witold-Barbara reservoir and showed uplift with a maximum rate of +9 mm/year. During this period, the reservoir was subjected to flooding (1995–1999). The ground surface over the southern part of the Victoria-Chrobry reservoir subsided with a maximum rate of −6 mm/a. During this period, the analyzed area was subjected to localized and periodic mining activity. Observations during the second period (1999–2002) showed uplift of the surface up to +8 mm/a. In the 2002–2010 period, uplift was observed in the central part of the basin. We believe that this phenomenon is mainly due to the combined effect of the restored water table levels in the Victoria-Chrobry and Julia reservoirs.

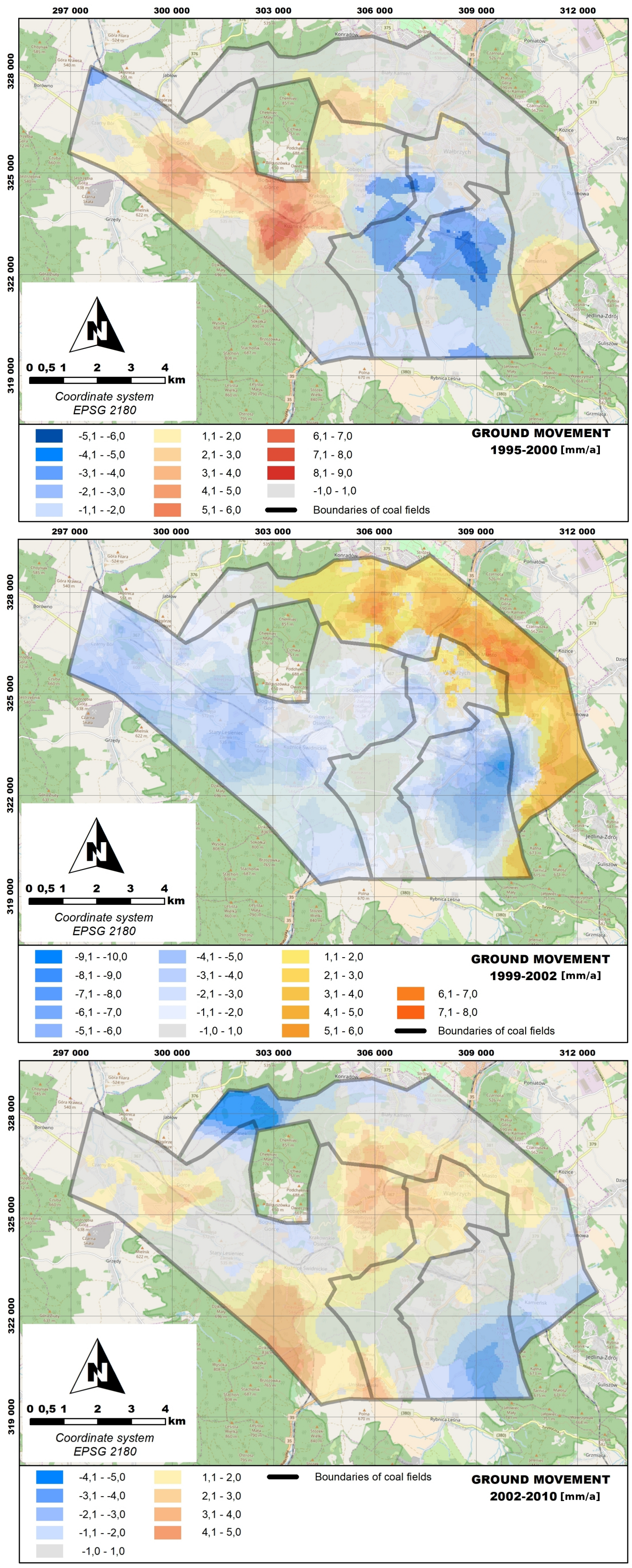

Figure 7. Mean annual ground movements for three calculation periods: 1995–2000 (top), 1999–2002 (middle), and 2002–2010 (bottom).

In order to demonstrate a complete state of ground movements in the investigated area over the period of 1995–2010, a draft view was plotted (Figure 8), with basic graphs of LOS displacements observed on selected, representative points. The selection of points was based on two assumptions. The first assumption was that each underground water reservoir must be represented by at least two points. The second assumption was that in the case of the Julia and Victoria-Chrobry reservoirs, more points should be selected for analysis, because a number of hydraulic connections exists between the two reservoirs. In addition, the reservoirs were flooded freely, with the exception of the controlled flooding of the Julia reservoir in the period of 1994–1998.

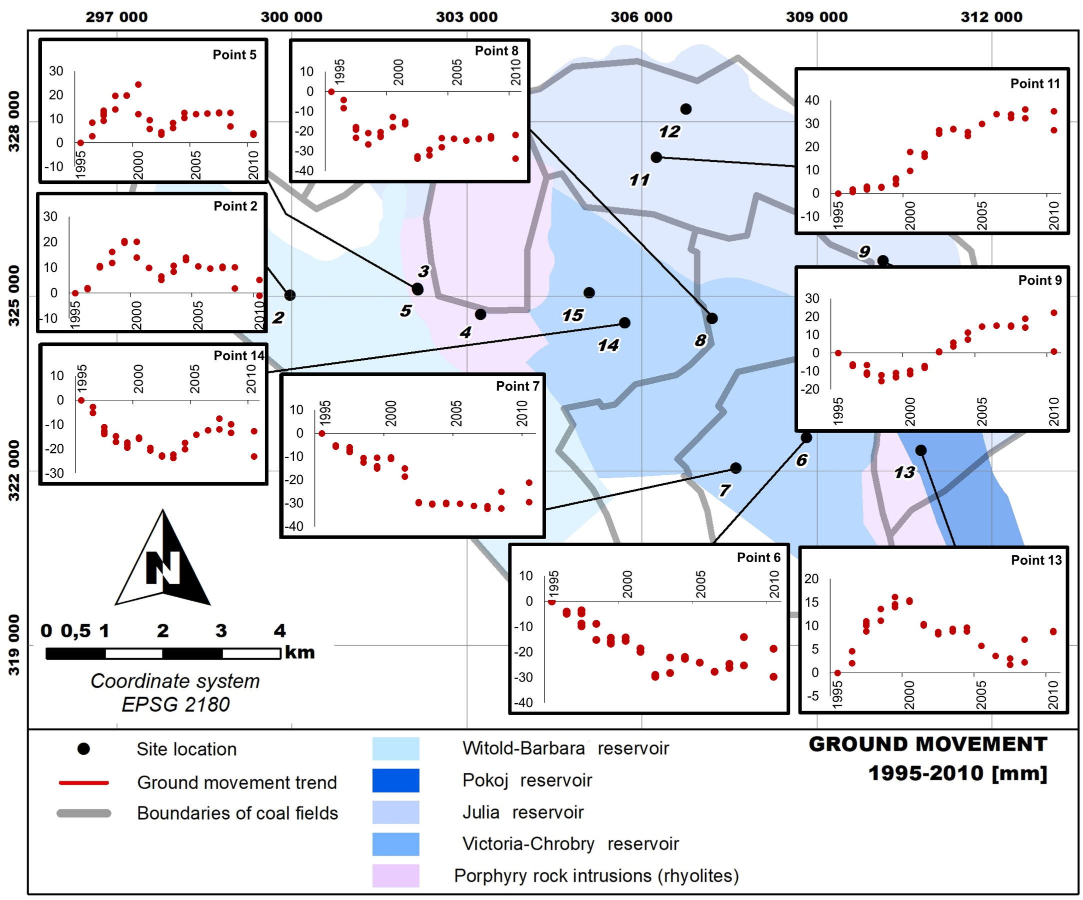

Figure 8. Location of the representative points, which served to plot LOS ground movement graphs between 1995 and 2010.

Points 2 and 5 in the Witold-Barbara reservoir showed uplift from the beginning of the analyzed period. Maximum uplift (approximately +20 mm) occurred in mid-1999. Restoration of the water table level in this reservoir started in November 1994. It seems justified to conclude that in this case, the observed movement results directly from the restoration of the water level in this area. However, the displacement trend observed after the period of maximum uplift in the area is an interesting phenomenon. Until the end of the analyzed period, total displacements oscillated around zero. This fact means that in 2010, the positions of Points 2 and 5 returned to those from 1995. The influence of the water table restoration in the Victoria-Chrobry reservoir was recorded at Points 6, 7, 8, 14, and 15 in the period from January to June 2000, i.e., about two years after the initiation of mine flooding. In the analyzed period ground surface subsided steadily in these locations. This trend changed to uplift in 2000. In comparison to upward movement in the Barbara-Witold area, the rates of uplift recorded in Locations 6, 7, 8, and 14 were much smaller. Movements calculated at Location 13 (the Pokoj reservoir) had a similar character to those recorded over the Witold-Barbara reservoir, as both reservoirs were flooded at the same time (June 2016). During the last years of exploitation in the basin, mining concentrated within the borders of support pillars. Displacements observed at Point 11 showed uplift since the beginning of the analyzed period. At that time, no extraction was carried out in the vicinity of this point. Displacements at Point 9, on the other hand, had a different nature. Between 1995 and 2000, a subsidence of −10 mm was observed. Later, the point was lifted in a very similar manner to Point 9.

Generally, the presented changes of ground movement values over time in the representative points show that depending on location, the process of ground deformations behaved differently. The analyses allowed us to conclude that the observed displacement trends are strictly related to the restoration of the underground water table in the four reservoirs. The phenomenon is discussed in detail in the following sections.

5. Discussion

In order to discuss in detail the results of the PSInSAR calculations, a series of graphs was plotted for 12 representative points in the coal basin area. The assumptions behind the choice of points have been provided in the Results Section. The graphs were based on data from three independent datasets (ERS 1/2 (1), ERS 1/2 (2), and Envisat). Different representative PS points were selected for each dataset with the assumption that the maximum difference in location between the first dataset, selected as the reference, and the remaining datasets is smaller than 0.006 degree of longitude or latitude. After the PSInSAR calculations, the displacement values were determined against the date for the master image. The ground movement values for each dataset were calculated (reduced) so that they represent the total displacement between the date of the first measurement and the date of each subsequent measurement. Additionally, the data from each set was matched with the data from the previous set. Finally, the value corresponding to the last date is equal to the absolute displacement recorded during the whole measurement period (from 1995–2005). The graphs of displacements in LOS for each point were combined with information on groundwater level change recorded in corresponding piezometers (marked with blue line; the vertical axis on the right corresponds to the water table height).

5.1. The Area of the Witold-Barbara Reservoir

In the case of the Witold-Barbara reservoir, the reaction of the ground surface to the restoration of the water table is clearly visible. All points in this area show upward movement, which for some time were convergent with the restoration of the water table from 100–380 m a.s.l. This process continued from October 1994 until October 1999 when the groundwater table level had stabilized. Interestingly, after the uplift process, the ground was observed to subside by approximately −15 mm (from 1999–2003). After 2003 the recorded ground movements remained within ±10 mm (Figure 9).

5.2. The Area of the Victoria-Chrobry Reservoir

A different process was observed in the case of the Victoria-Chrobry reservoir. The restoration of the groundwater table in this reservoir started in 1995, but in the first period of controlled flooding, the dynamics of water table rise was limited. As a consequence, the process was observed to have no direct influence on the ground surface. However, further ground subsidence was observed due to the final stages of exploitation of the remaining anthracite deposits. This operation was closed at the end of June 1998. The process of the water table restoration continued from February 1999–April 2002. In this period, the recorded ground movements in these locations pointed to decreasing subsidence and, as time progressed, a change to uplift. When the process of the water table restoration finished, the ground surface began to subside again. Only Point 15 showed a significant uplift (Figure 10). The reader should note that a similar situation occurred in the case of the Barbara-Witold reservoir.

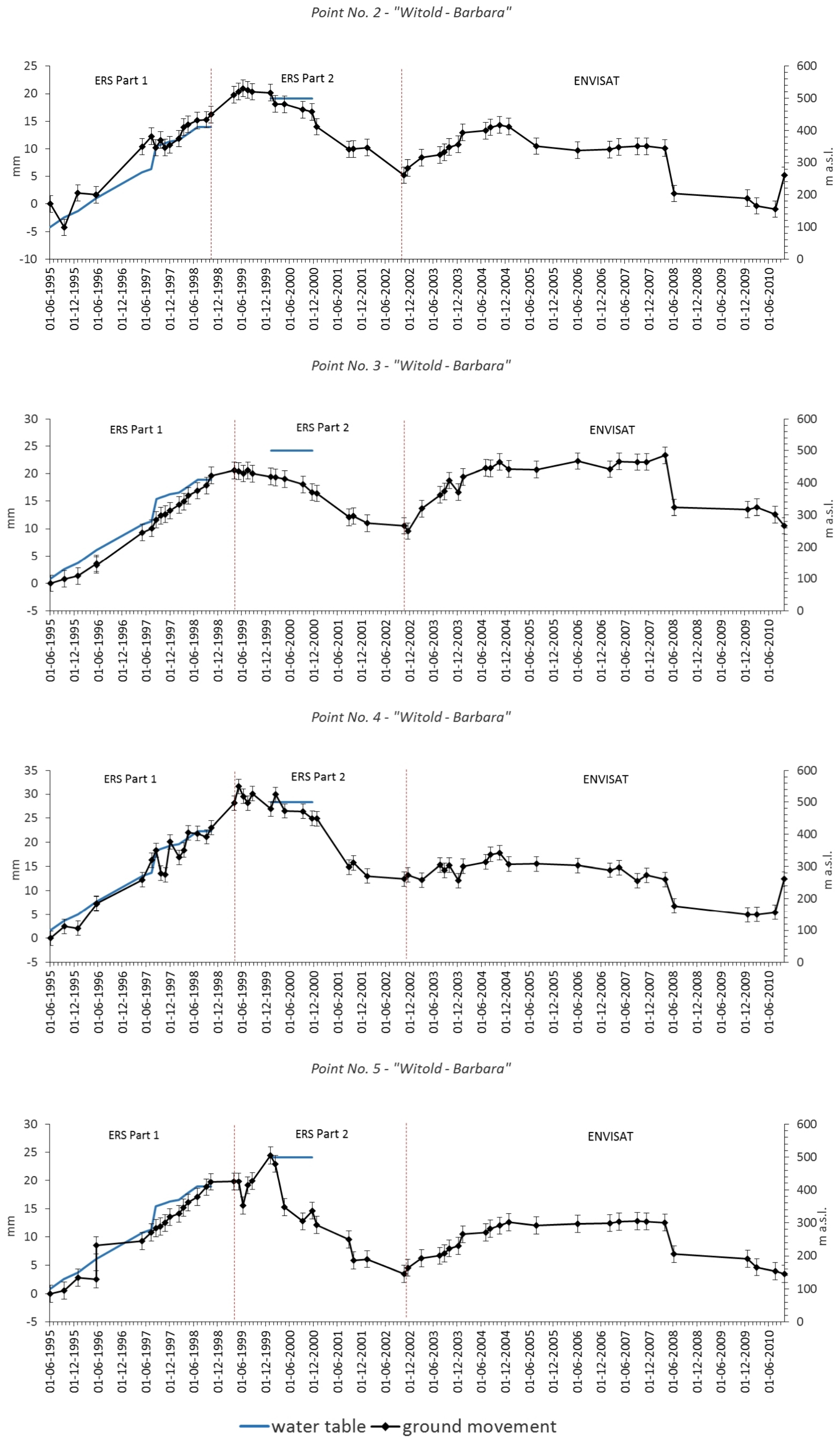

Figure 9. Graphs of LOS displacements for Points 2, 3, 4, and 5 located in the Witold-Barbara reservoir area.

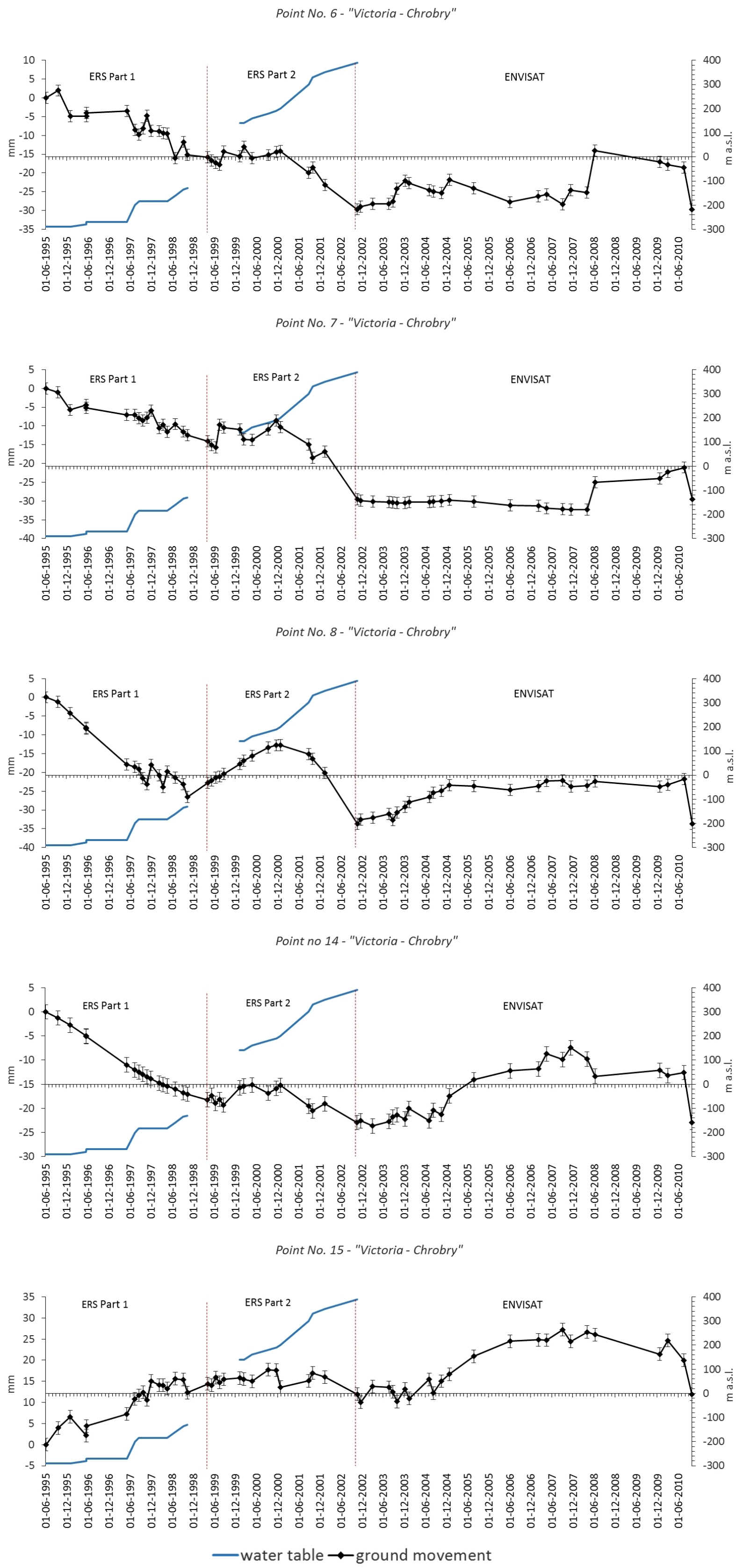

Figure 10. Graphs of LOS displacements for Points 6, 7, 8, 14, and 15 located over the Victoria-Chrobry reservoir.

5.3. The Area of the Julia Reservoir

Due to numerous hydraulic connections with the Victoria-Chrobry reservoir, the process of flooding the Julia reservoir was controlled and relatively slow during the first stage of its flooding. The dynamism of this process was practically identical as in the case of the Victoria-Chrobry reservoir. Movement of the ground during this period, recorded at Points 9 and 10 (Figure 11), was similar to the activity in the the Victoria-Chrobry reservoir area. The restoration of the water contributed to a smaller rate of subsidence in that period. During the period of the dynamic water table restoration, significant uplifts were recorded in the analyzed locations. Ground movements calculated for Location 12 in the 1996–1998 period demonstrate high variation, and this indicates the possible influence of atmospheric noise on these results.

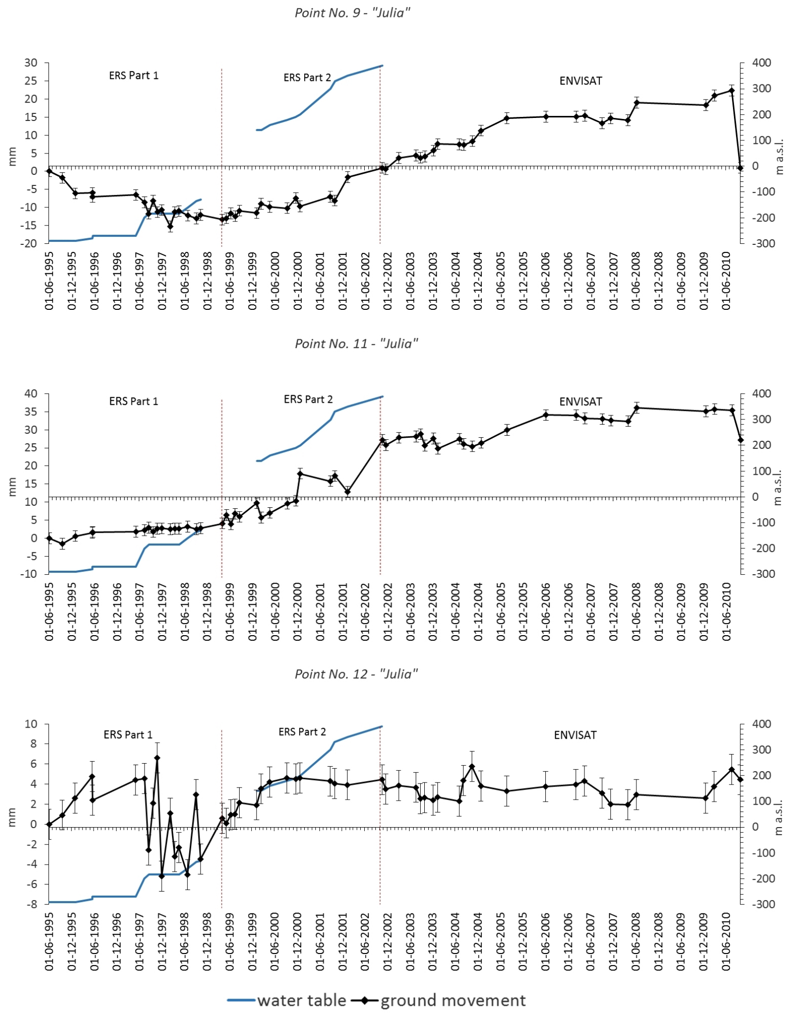

Figure 11. Graphs of LOS displacements for Points 9, 11, and 12 located over the Julia reservoir.

5.4. The Area of the Pokoj Reservoir

The process of flooding the Pokoj reservoir was faster than the flooding of the other analyzed reservoirs. Between June 1995 and May 1996, the water table rose by 205 m (Figure 12). However, such a dynamic increase of the underground water level did not result in equally dynamic changes on the ground surface. In the case of Point 10, records show slow surface uplift, which continued until the restoration process of the water conditions was completed. During this period, Point 13 indicated a more dynamic uplift process. The rock mass in the area of Point 13 was mined more intensively than in the area of Point 10.

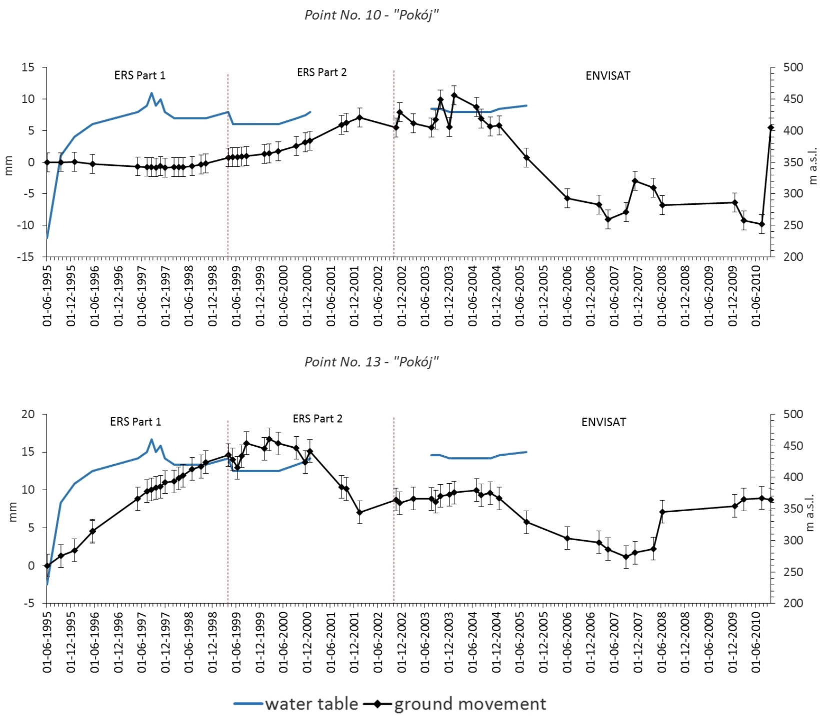

Figure 12. Graphs of LOS displacements for Points 9, 11, and 12 located over the Pokoj reservoir.

In addition, we performed hot spot analysis to identify locations with significant ground movements for three phases: ERS (1995–2000, 1999–2002), and Envisat (2002–2010). They are presented graphically in Figure 13. The hot spot analysis was done using the Getis–Ord Gi* Hot Spot and Global Moran's I spatial autocorrelation tools in ArcGIS software with the aim to determine areas with significant upward and downward ground movements (95% and 99% confidence). The principles of the methodology were given in [36,37]. Using PS locations with registered movements as input data, we calculated the standard deviations and probability values for each of these points. We used these values, standard deviations <−2.58 or >+2.58 with associated probability values <0.01 (99% confidence level) and standard deviations <−1.96 or >+1.96 with associated probability values <0.05 (95% confidence level) to determine clusters of PS points with statistically-significant values of upward and downward movements in the 1995–2010 period. These results indicate the most active zones and are shown graphically in Figure 13.

For the 1995–2000 data, a statistically-significant upward movement in relation to the entire dataset occurred in the Witold-Barbara underground water basin (represented by red dots) and statistically-significant subsidence in the central part of the Victoria-Chrobry basin (represented in blue, Figure 13, top). In the Victoria-Chrobry reservoir (associated with the Walbrzych mine), a decrease in mining activity had taken place. The rate of movement for this period was given in partial results and presented graphically in Figure 7.

In the 1999–2002 period, a statistically-significant upward movement in relation to the entire dataset was identified on a large area of the Julia underground water basin boundaries, which is represented by red dots. Local areas of statistically-significant subsidence are visible in the Witold-Barbara basin and eastern part of the Victoria-Chrobry basin, represented by blue dots (Figure 13, middle). The rate of movement for this period is given in partial results and presented graphically in Figure 7.

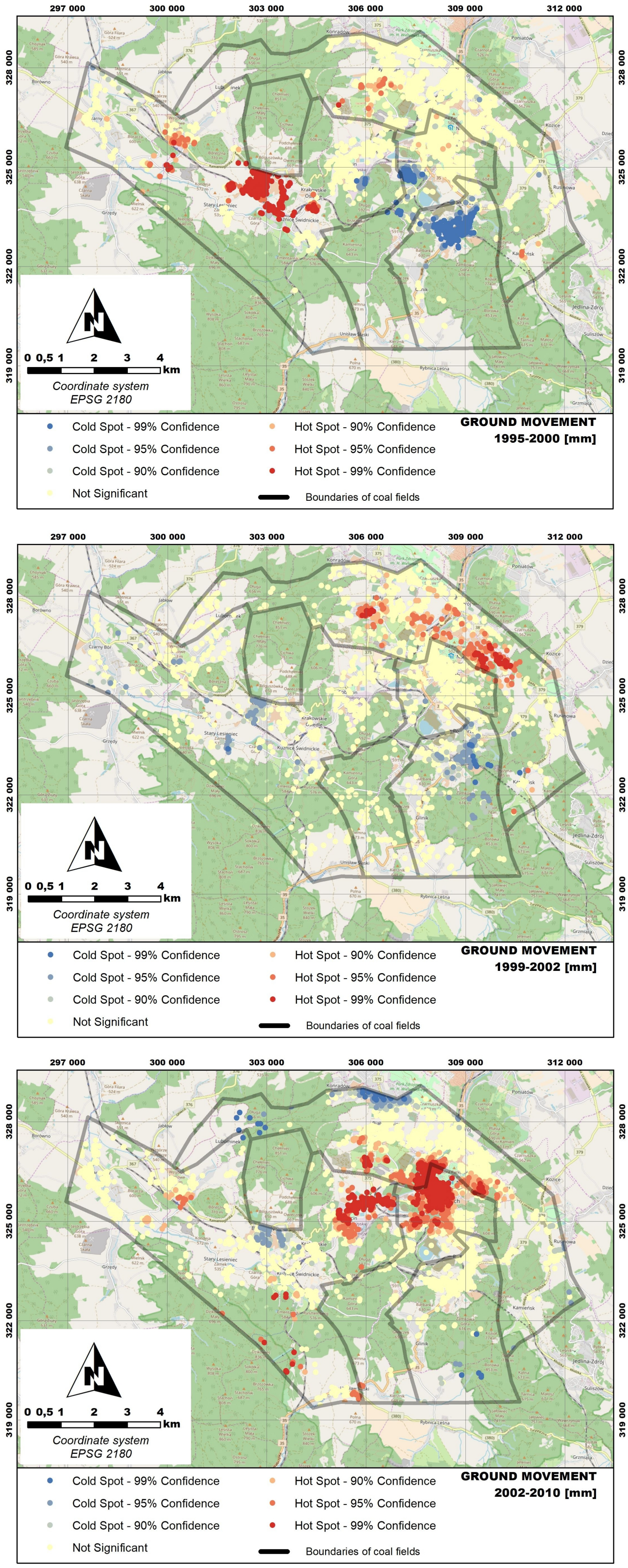

Figure 13. Calculated hot spots for the three calculation periods: 1995–2000 (top), 1999–2002 (middle), and 2002–2010 (bottom).

In the 2002–2010 period, i.e., after the ground water level rise was completed, a statistically-significant upward movement is visible in the central part of the Walbrzych coal fields in parts of the Witold-Barbara, Julia and Victoria-Chrobry underground water reservoirs and represented by red dots (Figure 13, bottom). The small areas of significant upward and downward movements in the Witold-Barbara basin could probably be attributed to the local effects of mining. The rate of movement for this period is given in partial results and presented graphically in Figure 7. The cause of statistically-significant subsidence in the northern part of the study area—blue dots—is not related to mining and is presently unknown.

The phenomenon of post-mining ground surface and subsidence is referred to as secondary deformations [38,39]. Phenomena similar to those observed in the Walbrzych region were observed with the use of the InSAR methods also in France, Germany, Belgium, and England [1,2,11]. The application of InSAR methods in the detection of ground surface activity in post-mining areas was also discussed in [40–43].

The results obtained for the WHCB region are similar to the results obtained for the Limburg region (Germany) [1]. This similarity covers not only the recorded scale of upward movements, but also the dynamic characteristics of the phenomenon. The presented results, as is the case in the WHCB region, clearly indicate a direct correlation between rising underground water levels and upward movements of post-mining grounds. A similar ground surface movement was observed in Northumberland [11]. In some cases (e.g., the Westoe region), the results of ground movements calculated from ERS 1/2 did not correlate with hydrogeological data. An interesting observation comes from [2], who noticed that in the case of the observed uplifts in the post-mining areas of the French-German border region, the movements were not always located directly over the flooded workings. This fact is due to the geological and tectonic structure and to the spatial arrangement of roadways and workings. With this observation applied to the conditions of the WHCB area, a conclusion can be made that a specific geological structure and local tectonic faults caused the influence of the flooded reservoir to be always observed directly over the reservoir.

6. Conclusions

Underground hard coal mining in the Walbrzych region dates back to the 15th Century. As a result of such a long period of human intervention in the rock mass, total ground subsidence due to coal extraction was estimated to reach −22 m [15]. The Walbrzych operations were the first in Poland and one of a few in Europe to be completely closed in such a short period of time. Additionally, when mining activity was stopped, underground water levels were no longer regulated. This marks the beginning of the process of underground water table restoration.

Our study provided information based on processed SAR data on the behavior of ground surface after the end of mining. We demonstrated the differentiated spatial character of ground movements in the basin associated with the three coal mines that were flooded separately. This is unique for the Walbrzych site and differs from other coal mining regions analyzed in the literature. We have identified three distinct stages of ground surface movements, elevation, subsidence, and stabilization, within the analyzed 15-year period. Because of the controlled and partly-controlled process of ground water restoration, each of the parts in the basin followed the process of ground uplift, subsidence, and stabilization at a different time. We determined the relationship between flooding of underground water reservoirs and uplift of the ground, a process that has also been established in other examples taken from the literature and presented in the Introduction Section.

However, we also observed that controlled flooding of post-mining workings carried out over a relatively long period of time minimized the effects of the process on the ground surface. The maximum rate of elevation in the first phase reached 33 mm, calculated for the Witold-Barbara reservoir area, whereas the maximum rate of subsidence in the second stage reached −26 mm in the Witold-Barbara reservoir area. The analyses in this paper prove that the period of ground upward movement, directly related to the restoration of the groundwater table level, is followed by a short period of stagnation and then by a sort of ground movement adjustment. This adjustment is characterized by ground subsidence and followed by eventual stabilization of the surface. We suggest that the area should be monitored in the future due to the facts that these movements have not stopped completely and the area is characterized by shallow (close to the surface) workings that are prone to destruction and may cause continuous and discontinuous deformation on the surface.

Author Contributions: J.B., review and editing, conceptualization, formal analysis, and validation; A.K., visualization; W.M., investigation, original draft preparation, conceptualization, supervision, methodology, and software; K.O., original draft preparation and resources.

Acknowledgments: This work was supported by the Ministry of Science and Higher Education statutory grant realized at the Faculty of Geoengineering, Mining and Geology, Wroclaw University of Science and Technology.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cuenca, C.M.; Hooper, A.J.; Hanssen, R.F. Surface deformation induced by water influx in the abandoned coal mine in Limburg, The Netherlands observed by satellite radar interferometry. *J. Appl. Geophys.* **2013**, *88*, 1–11. [CrossRef]
2. Samsonov, S.; D'Oreye, N.; Smets, B. Ground deformation associated with post-mining activity at the French–German border revealed by novel InSAR time series method. *Int. J. Appl. Earth Observ. Geoinf.* **2013**, *23*, 142–154. [CrossRef]
3. Raucoules, D.; Bourgine, B.; de Michele, M.; Le Cozanet, G.; Closset, L.; Bremmer, C.; Veldkamp, H.; Tragheim, D.; Bateson, L.B.; Crosetto, M.; et al. *PSIC4 Persistent Scatterers Interferometry Independent Validation and Intercomparison of Results*; Technical Report June; Bureau de Recherches GéOlogiques et MinièRes: Orléans, France, 2007.
4. Perski, Z. Applicability of ERS-1 and ERS-2 InSAR for land subsidence monitoring in the Silesian coal mining region, Poland. *Int. Arch. Photogramm. Remote Sens.* **1998**, *32*, 555–558.
5. Ge, L.; Rizos, C.; Han, S.; Zebker, H.A. Mining Subsidence Monitoring Using the Combined Insar and Gps Approach. In Proceedings of the 10th International Symposium on Deformation Measurements, Orange, CA, USA, 19–22 March 2001.
6. Wegmuller, U.; Werner, C.; Strozzi, T.; Wiesmann, A. Monitoring mining induced surface deformation. In Proceedings of the 2004 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2004), Anchorage, AK, USA, 20–24 September 2004; Volume 3, pp. 1933–1935. [CrossRef]
7. Baek, J.; Kim, S.W.; Park, H.J.; Jung, H.S.; Kim, K.D.; Kim, J.W. Analysis of ground subsidence in coal mining area using SAR interferometry. *Geosci. J.* **2008**, *12*, 277–284. [CrossRef]
8. Bateson, L.; Lawrence, D.; Cigna, F.; Mccormack, H.; Burren, R. Ground Motion in Areas of Abandoned Mining: A Case Study of PSI Applied to The Northumberland Region of The UK. In Proceedings of the Conference on ESA Living Planet Symposium, Edinburgh, UK, 9–13 September 2013.
9. Abdikan, S.; Arikan, M.; Sanli, F.B.; Cakir, Z. Monitoring of coal mining subsidence in peri-urban area of Zonguldak city (NW Turkey) with persistent scatterer interferometry using ALOS-PALSAR. *Environ. Earth Sci.* **2014**, *71*, 4081–4089. [CrossRef]
10. Vervoort, A.; Declercq, P.Y. Surface movement above old coal longwalls after mine closure. *Int. J. Min. Sci. Technol.* **2017**, *27*, 481–490. [CrossRef]
11. Gee, D.; Bateson, L.; Sowter, A.; Grebby, S.; Novellino, A.; Cigna, F.; Marsh, S.; Banton, C.; Wyatt, L. Ground Motion in Areas of Abandoned Mining: Application of the Intermittent SBAS (ISBAS) to the Northumberland and Durham Coalfield, UK. *Geosciences* **2017**, *7*, 85. [CrossRef]
12. Chaussard, E.; Milillo, P.; Bürgmann, R.; Perissin, D.; Fielding, E.J.; Baker, B. Remote Sensing of Ground Deformation for Monitoring Groundwater Management Practices: Application to the Santa Clara Valley During the 2012–2015 California Drought. *J. Geophys. Res. Solid Earth* **2017**, *122*, 8566–8582. [CrossRef]
13. Riel, B.; Simons, M.; Ponti, D.; Agram, P.; Jolivet, R. Quantifying Ground Deformation in the Los Angeles and Santa Ana Coastal Basins Due to Groundwater Withdrawal. *Water Resour. Res.* **2018**, *54*, 3557–3582. [CrossRef]

14. Kominowski, K. Geology and Hydrogeology. In *Mining and surface protection. Experiences from the Walbrzych Mines*; Kowalski, A., Ed.; Central Mining Institute: Katowice, Poland, 2000; Chapter 3, pp. 33–48. (In Polish)
15. Kowalski, A. First experiences with surface protection. Geodetic network for deformation measurements. In *Mining and Surface Protection. Experiences from the Walbrzych Mines*; Kowalski, A., Ed.; Central Mining Institute: Katowice, Poland, 2000; Chapter 5, pp. 109–111. (In Polish)
16. Fiszer, J.; Sawicki, J.; Czaba, W.; Jerz, U. *Analysis of Flooding Process of Wałbrzych Mines and Assessment of Its Impact on the Environment*; Technical Report; Hydros: Oborniki Slaskie, Poland, 2000. (In Polish)
17. Fiszer, J.; Gogolewska, A. *Changes of Groundwater Conditions during the Process of Lower Silesian Coal Basin Closure*; Technical Report; Wroclaw University of Technology, Institute of Mining Engineering: Wroclaw, Poland, 2003. (In Polish)
18. Hooper, A.; Bekaert, D.; Spaans, K.; Arıkan, M. Recent advances in SAR interferometry time series analysis for measuring crustal deformation. *Tectonophysics* **2012**, *514–517*, 1–13. [CrossRef]
19. Kampes, B.; Usai, S. Doris: The Delft objectoriented Radar Interferometric Software. In Proceedings of the ITC 2nd ORS Symposium, Enschede, The Netherlands, 16–20 August 1999.
20. Chen, C.W.; Zebker, H.A. Network approaches to two-dimensional phase unwrapping: intractability and two new algorithms. *J. Opt. Soc. Am. A* **2000**, *17*, 401–414. [CrossRef]
21. Farr, T.; Rosen, P.; Caro, E.; Crippen, R.; Duren, R.; Hensley, S.; Kobrick, M.; Paller, M.; Rodriguez, E.; Roth, L.; et al. The shuttle radar topography mission. *Rev. Geophys.* **2007**, *45*, 1–33. [CrossRef]
22. Hooper, A.; Segall, P.; Zebker, H. Persistent scatterer interferometric synthetic aperture radar for crustal deformation analysis, with application to Volcán Alcedo, Galápagos. *J. Geophys. Res. Solid Earth* **2007**, *112*. [CrossRef]
23. Berardino, P.; Fornaro, G.; Lanari, R.; Sansosti, E. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Trans. Geosci. Remote Sens.* **2002**, *40*, 2375–2383. [CrossRef]
24. Lanari, R.; Casu, F.; Manzo, M.; Zeni, G.; Berardino, P.; Manunta, M.; Pepe, A. An Overview of the Small BAseline Subset Algorithm: A DInSAR Technique for Surface Deformation Analysis. *Pure Appl. Geophys.* **2007**, *164*, 637–661. [CrossRef]
25. Casu, F. The Small BAseline Subset Technique: Performance Assessment and New Developments for Surface Deformation Analysis of Very Extended Areas. Ph.D. Thesis, University of Cagliari, Cagliari, Italy, 2009.
26. Nadudvari, A. Using radar interferometry and SBAS technique to detect surface subsidence relating to coal mining in Upper Silesia from 1993–2000 and 2003–2010. *Environ. Socio-Econ. Stud.* **2016**, *4*, 24–34. [CrossRef]
27. Grzovic, M.; Ghulam, A. Evaluation of land subsidence from underground coal mining using TimeSAR (SBAS and PSI) in Springfield, Illinois, USA. *Nat. Hazards J. Int. Soc. Prev. Mitig. Nat. Hazards* **2015**, *79*, 1739–1751. [CrossRef]
28. Fan, H.; Lu, L.; Yao, Y. Method Combining Probability Integration Model and a Small Baseline Subset for Time Series Monitoring of Mining Subsidence. *Remote Sens.* **2018**, *10*, 1444. [CrossRef]
29. Gudmundsson, S.; Carstensen, J.M.; Sigmundsson, F. Unwrapping ground displacement signals in satellite radar interferograms with aid of GPS data and MRF regularization. *IEEE Trans. Geosci. Remote Sens.* **2002**, *40*, 1743–1754. [CrossRef]
30. Xu, X.; Sandwell, D.T.; Tymofyeyeva, E.; González-Ortega, A.; Tong, X. Tectonic and Anthropogenic Deformation at the Cerro Prieto Geothermal Step-Over Revealed by Sentinel-1A InSAR. *IEEE Trans. Geosci. Remote Sens.* **2017**, *55*, 5284–5292. [CrossRef]
31. Farolfi, G.; Bianchini, S.; Casagli, N. Integration of GNSS and Satellite InSAR Data: Derivation of Fine-Scale Vertical Surface Motion Maps of Po Plain, Northern Apennines, and Southern Alps, Italy. *IEEE Trans. Geosci. Remote Sens.* **2019**, *57*, 319–328. [CrossRef]
32. Motagh, M.; Djamour, Y.; Walter, T.R.; Wetzel, H.U.; Zschau, J.; Arabi, S. Land subsidence in Mashhad Valley, northeast Iran: results from InSAR, leveling and GPS. *Geophys. J. Int.* **2007**, *168*, 518–526. [CrossRef]
33. Milczarek, W.; Blachowski, J.; Grzempowski, P. Application of PSInSAR for assessment of surface deformations in post-mining area—Case study of the former Walbrzych hard coal basin (SW Poland). *Acta Geodyn. Geomater.* **2017**, *14*, 41–52. [CrossRef]
34. Blachowski, J.; Jiránková, E.; Lazecký, M.; Kadlečík, P.; Milczarek, W. Application of satellite radar interferometry (PSInSAR) in analysis of secondary surface deformations in mining areas. Case studies from Czech Republic and Poland. *Acta Geodyn. Geomater.* **2018**, *15*, 173–185. [CrossRef]

35. Blachowski, J.; Milczarek, W. Analysis of surface changes in the wałbrzych hard coal mining grounds (sw Poland) between 1886 and 2009. *Geol. Q.* **2014**, *58*, 353–368. [CrossRef]
36. Getis, A.; Ord, J.K. The Analysis of Spatial Association by Use of Distance Statistics. *Geogr. Anal.* **1992**, *24*, 189–206. [CrossRef]
37. Ord, J.K.; Getis, A. Local Spatial Autocorrelation Statistics: Distributional Issues and an Application. *Geogr. Anal.* **1995**, *27*, 286–306. [CrossRef]
38. Fenk, J. An analytical solution describing the uplift of surface occurring during the liquidation of mines by dumping. *Pol. Min. Rev.* **1999**, *11*, 12–14. (In Polish)
39. Pottgens, J.J.E. Bodenhebung durch ansteigendes Grubenwasser [Uplift as result of rising mine waters]. The Development Science and Art of Minerals Surveying 2. In Proceedings of the 6th Inernational Congress International Society for Mine Surveying, Harrogate, UK, 9–13 September 1985. (In German)
40. Salmi, E.F.; Nazem, M.; Karakus, M. The effect of rock mass gradual deterioration on the mechanism of post-mining subsidence over shallow abandoned coal mines. *Int. J. Rock Mech. Min. Sci.* **2017**, *91*, 59–71. [CrossRef]
41. Jordan, H.; Cigna, F.; Bateson, L. Identifying natural and anthropogenically-induced geohazards from satellite ground motion and geospatial data: Stoke-on-Trent, UK. *Int. J. Appl. Earth Observ. Geoinf.* **2017**, *63*, 90–103. [CrossRef]
42. Sheng, Y.; Wang, Y.; Ge, L.; Rizos, C. Differential radar interferometry and its application in monitoring underground coal mining-induced subsidence. In Proceedings of the International Conference on Geo-spatial Solutions for Emergency Management and the 50th Anniversary of the Chinese Academy of Surveying and Mapping, Beijing, China, 14–16 September 2009.
43. Milczarek, W.; Blachowski, J. Analysis of mining deformations based on PSInSAR technique—Case study of the Walbrzych coal mines, Poland. In Proceedings of the 16 th International Congress for Mine Surveying, Brisbane, Australia, 12–16 September 2016.