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REVIEW ON THE USE OF SATELLITE-BASED RADAR INTERFEROMETRY FOR MONITORING MINING SUBSIDENCE IN URBAN AREAS AND DEMOGRAPHIC INDICATORS ASSESSMENT

Alina RADUTU[1], Maria-Ioana VLAD-SANDRU[2]*

[1] Romanian Space Agency, Bucharest, Romania, alina.radutu@rosa.ro
[2] Romanian Space Agency, Bucharest, Romania, ioana.vlad@rosa.ro

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Abstract: *Mining activities represent one of the main causes leading to subsidence in the natural and urban environment. Sustainable urban planning and detection of potential hazards in mining areas involve the use of adequate instruments such as the continuous monitoring of land subsidence. The complexity of urban environment demands the utilization of new methods for monitoring and quantifying the effects of the mining processes. In the last decades, considering the technological developments from the remote sensing domain, the Synthetic Aperture Radar Interferometry (InSAR) techniques offer the opportunity for early detection and continuous monitoring of subsidence in mining areas, including urban centers. Considering various parameters of mining subsidence monitoring, a review of several tens of studies realized in different mining sites, based on InSAR techniques, is presented. As mining subsidence in urban areas has a direct impact on the quality of life, the review is completed with demographic indicators assessment, followed by a study case on the dynamics of the population in an urban mining area from Romania, Ocnele Mari.*
Keywords: *InSAR, subsidence, mines, monitoring, remote sensing, demographic indicators*

1. Introduction

Land subsidence is a ground surface degradation form affecting the natural and anthropic environment. Mining activities represent one of the main causes leading to slow or rapid ground deformation. Unless many mines were established initially in wild landscape areas outside human settlements [1], the long-term mining exploitation works led to the development of urban centers in those areas. Besides these situations, in the case of abandoned underground mines, humans have expanded to occupy the formerly wild landscape [2]. As a consequence of the exploitation works and of the constantly changes occurring even in the historical closed mines, the urban centers can be affected by land subsidence. In some cases, the consequences of mining subsidence can be reflected in the dynamics of the population from the area.

Sustainable urban planning and detection of potential hazards involve the use of adequate instruments such as the continuous monitoring of land subsidence [3]. Conventional methods for mining subsidence monitoring, demonstrating high accuracy, are precise levelling and GNSS (Global Navigation Satellite Systems) surveys [4]. In the last decades, considering the constraints of each of these methods [5] and the technological developments from the remote sensing domain, the Synthetic Aperture Radar Interferometry (InSAR) techniques offer the opportunity for early detection and continuous monitoring [6] of mining subsidence in urban areas. An evolution of InSAR techniques took place during these last decades as new radar satellite missions were launched and the storage and processing capacity of SAR acquisitions increased [7], leading to better achievements in terms of accuracy of land subsidence monitoring [8]. Although a wide range of studies focuses on the use of these techniques, for the best results or for validation, it is recommended that InSAR techniques to be used in conjunction with other monitoring techniques [9].

This review focuses on the collection and analysis of scientific literature that uses InSAR approaches for monitoring mining areas, especially including urban areas. Characteristics such as country, type of mining

* Corresponding author: Alina Radutu, Research Engineer, Romanian Space Agency, Bucharest, Romania, contact details: Mendeleev Str. 21-25, +40213168722, +40213128804, www.rosa.ro, alina.radutu@rosa.ro

exploitation, status of the mining area when the SAR monitoring was performed, SAR monitoring technique, deformation rate, SAR monitoring period, SAR data used for mining subsidence monitoring, the alternative monitoring methods complementary used to InSAR methods. Considering the consulted scientific literature on this topic and the wide spread of different types of mining worldwide, it can be stated that in many cases the most challenging areas were chosen to be monitored, considering the accidents [10] or the complexity of the studied areas [11-13]. Long-term SAR monitoring analyses are also of interest, considering the open SAR data available since 1992 [14]. As mining subsidence in urban areas has a direct impact on the quality of life, a complementary assessment brings demographic characteristics in a study case which is focused on the dynamics of the population in Ocnele Mari-mining area, Romania.

2. Materials and methods

More than 30 mining areas are presented in this review, where more than 40 study cases were considered, covering different types of mines, and different monitoring time intervals from 1992 to 2023. Year 1992 represents the starting moment of long multi-temporal SAR analyses, as the first satellite mission including an imaging Synthetic Aperture Radar (SAR), which provided enough suitable data for interferometry was the ERS-1 (European Remote Sensing) satellite [15], launched in July 1991. The longest time evolution of mining subsidence monitoring using InSAR was made in Belgium, for three decades [16].

First part of this section describes briefly the InSAR techniques applied for the different monitored mining subsidence areas, followed in the second part by demographic indicators assessment.

2.1. InSAR approaches used for monitoring mining subsidence urban areas

The evolution of the InSAR techniques could be revealed by the reviewed scientific literature, articles on the topic of InSAR methods used for monitoring mining subsidence being available from 1997 [17] until today [16].

- Classical InSAR technique

Interferometric SAR (InSAR), is a measuring technique dating back to the 1970s, which became popular in the 1990s, when European Space Agency (ESA) launched the ERS-1 mission [15]. Data acquisition is made by coherent active sensors, using as illuminating source the microwave energy, which have day and night operational capabilities, regardless the weather conditions [18]. The SAR systems acquire information both in amplitude and phase. SAR interferometry is exploiting the phase difference of two acquisitions made on the same area at different time moments, from almost the same look angle, generating an interferogram [19]. The distance between the two acquisition orbits is a known distance named baseline [15]. In radar interferometry the first image from the interferometric pair is named the master scene and the second is the slave scene [19]. The SAR interferogram is generated by multiplying the first SAR image with the complex conjugate of the second one [18]. The interferometric phase is the phase difference between the two scenes, while the interferogram amplitude is the amplitude of the first scene multiplied with the amplitude of the second one [18]. The phase difference represents the interferometric fringes, excluding the terrain phase, flat earth phase, atmospheric phase and noise phase effects [20]. The interferometric fringe is used to extract information relative to vertical height changes on the Earth's surface [21]. The presence of the vegetation leading to the appearance of decorrelations, large baselines, long time period between two acquisitions and system noise [18,19] are some of the most relevant limitations of InSAR. Therefore, in the study cases where InSAR was used as mining subsidence monitoring technique, a special importance was given to the appropriate image selection, for minimizing the influence of the possible errors [21]. The classical InSAR approach was used for subsidence mining monitoring in [21,22].

- DInSAR Technique

Based on InSAR principles, if multiple SAR scenes acquired with the same geometry, at different time moments are available for a study area, the effects of the topographic component and of other factors can be removed from the differential interferometric phase, and the vertical terrain motion component can be measured [18]. This is also available if an external DEM is used for subtracting the topographic component from the interferometric phase [18]. This technique represents the Differential SAR Interferometry (DInSAR). One of the limitations of this technique is related to the presence of the atmospheric effect in the final result [23]. DInSAR was used for mining subsidence monitoring in [10, 24-38].

- MTI or A-DInSAR or TS-InSAR techniques

For the estimation and correction of residual atmospheric phase, DEM errors, sub-pixel target position related phase offsets, and the loss of coherence, new InSAR techniques were developed, considering long temporal series of SAR data [23] to generate time series of deformation [39]. These are the Multi-Temporal Interferometry (MTI) or Advanced- Differential SAR Interferometry (A-DInSAR) or Time-Series InSAR (TS-InSAR). Considering the characteristic stated above, many A-DInSAR or MTI or TS-InSAR techniques were developed during last two decades. These techniques can be divided into more categories considering the categories of backscaterrer used for SAR data processing [31]. As more A-DInSAR or TS-InSAR techniques were used in the reviewed literature for mining subsidence monitoring, each type of backscaterrer will be defined for the specific technique. First A-DInSAR technique is PSI, presented below.

- PSI Technique

The main difference between this technique and the previous ones (InSAR and classical DInSAR) is the generation of multiple SAR interferograms (minimum 15-20 interferograms for C-band) [40]. Natural highly reflective stable ground features characterized by reliable amplitude and coherent signal phase over all SAR scenes are identified in the interferograms and used for data processing [23,41]. These are the permanent or persistent scatterers (PSs). PSI measurements are made in the line-of sight (LOS), and one of its particularities is that all datasets are registered to a unique master scene [40]. Permanent scatterers are revealing the displacements in the time series of the studied area, relatively to a reference point [41].

Unlike the previous methods, for PSI the atmospheric phase contributions are removed, all available radar data can be used regardless the geometrical baseline, good phase coherence can be achieved using the available data [42], and accuracies of millimetric level are obtained [18]. PSI technique was used for mining subsidence monitoring in [13,14,16,25,26,33,39,43-52].

- SBAS Technique

The Small Baseline Subset (SBAS) and related methods are part of MTI techniques class. SBAS methods are focusing on pairs of interferograms characterized by small spatial baselines [53] for using more spatially dispensed information. The SBAS concentrates on distributed scatterers, as they are more sensible to temporal and volume decorrelation than PSs [23]. SBAS technique was used for mining subsidence monitoring in [12-14,20,28,54].

- SqueeSAR Technique

Based on the PSI processing chain, [55] developed a new interferometric technique which is using both PSs and Distributed Scatterers (DSs). If PSs are coherent targets with high phase stability during the processing time interval, DSs are characterized by moderate coherence, and usually they are sharing the same reflectivity values as their neighbours, considering that they are belonging to the same object [56]. This new method named SqueeSAR, is jointly processing the two types of backscatterers, considering their different statistical behaviour [55,57]. This technique was used for mining subsidence monitoring in [11,58].

- CPT Technique

Coherent Pixels Technique (CPT) is an A-DInSAR technique allowing the isolation of the contribution of the different terms, part of the interferometric phase [59]. It is based on multi-looked interferograms and the pixels should have a coherence value higher than an assigned threshold [60]. [59] is using this method for mining subsidence monitoring.

- ISBAS Technique

Intermittent SBAS technique (ISBAS) represents a method which can bring better results for non-urban or rural areas, where coherence can be more easily lost due to the lack of coherent pixels along all considered processing time period. Hence, it uses also pixels coherent only for subsets of the total time period [61,62].

- QPS-PS InSAR Technique

Unlike PSI technique where the stable targets should be coherent during the whole observation span, the Quasi-PS InSAR (QPS-InSAR) technique allows the use during the multi-temporal analysis of the SAR images the extraction of information from partially coherent targets. This approach leads to the increase of the spatial coverage of the estimate of height and deformation trend, particularly in extra-urban areas [63].

2.2. Demographic characteristics and description of the test site

For the human settlements found in the mining exploitation areas, there are analysed demographic indicators, which are influenced by the local industries challenges during a determined period of time.

A significant importance of population characteristics goes to the size and the rate at which it is expanding or contracting, focusing on the evolution of the birth rate (BR) and death rate (DR), both aggregated in population natural increase rate (NIR), obtained from the difference between birth and death rate. Birth rate is the number of people born in a population in a given amount of time, while the death rate is the number of deaths, per year, varying, due to differences in living standards and economic conditions. The natural increase rate measures the population trend in the way it's growing or declining.

The birth rate represents the ratio between the total number of birth (B) and the number of the population (P) per 1000 inhabitants, while the death rates is the ratio between the total number of death (D) and the number of the population per 1000 inhabitants.

$$BR = (B/P) \times 1000 \quad (1)$$

$$DR = (D/P) \times 1000 \quad (2)$$

The population natural increase rate (NIR) states the difference between birth (BR) rate and death rate (DR).

$$NIR = BR - DR \quad (3)$$

However, the natural increase rate (NIR) does not reflect the total number of the population, being determined just by the difference between birth and death rates in a given region, excepting total population arrivals and total population departures.

In order to have a broader demographic dynamic assessment, the natural increase rate is merged with the effects of migration, which result in the total population dynamic, represented by the sum of the following variables: the difference between number of birth (B) and number of deaths (D), together with the difference between the number of immigrants and emigrants

2.3. Description of the test site

Mining bring benefits to national economies in many countries, by contribution to national GDP and to creating jobs [64]. On the other hand, the mineral resources can generate negative environmental and social impacts, holding down the achievement of the sustainable development goals (climate action, good health, clean water) [65], and depopulation trends. The aim of this analysis is to explore the most relevant demographic characteristics from a Romanian mining urban area, Ocnele Mari.

Ocnele Mari is located in the central-southern part of Romania, in the Getic Sub-Carpathians area, in the Topologului Valley and Bistrita Valley sector, Valcea County [66]. The salt deposits has been exploited since Roman Times [67], as the local lithology is represented by diapir folds, with the salt massif reaching the surface through the Ocnele Mari-Ocnița anticline [66]. The salt deposit is about 8 km long, with thicknesses up to 400 m [68]. As initially salt was exploited only for food, at the beginning of 19th century, the curative qualities of salt waters stated to be used through spa resorts [66]. In 1960 the Teica Mare field was open and about 2 million tons of salt have been exploited from it, through the dissolution process in wells, mainly for industrial purposes [67]. As a consequence, the current geomorphological processes have a high dynamic, the salt mining field being at risk of extensive collapsing since 1968, when the first sign of surface damage occurred [69].

The local population size assessment is illustrated starting with 1992, when the old mine was closed and a new salt mine was open at Cocenesti working point, located in the Eastern part of Ocnele Mari and of the old mine [70].

The population data sets necessary for the demographic characteristics analysis were provided by the National Institute of Statistics in Romania [71].

3. Exploring the characteristics of the InSAR monitoring of mining subsidence areas correlated with demographic indicators analyses

Table 1 summarizes the general characteristics of the mining subsidence areas monitored by InSAR techniques. In the following sections, the different characteristics of the subsiding mining areas are analysed.

Table 1. General characteristics of mining subsidence areas monitored by InSAR techniques

Mining area	Type of mine	Monitoring period	SAR technique	Radar satellite data	Deformation rate	Other monitoring method used	Urban areas
Roncourt, Lorraine, France [43]	Iron mining, historical mining activity	1995-2000	PSI	ERS-1/2	5 cm	Levelling measurements	Roncourt
Gardanne, France [24]	Underground coal mining-active mine	1992-1995	DInSAR	ERS1/2, 12 scenes	Migration of the subsidence halo	Field geodetic measurements	Gardanne
Nord/Pas-de-Calais, France [25,72]	Underground coal mining closed since 1992	1992-2004	DInSAR & PSI	ERS 1/2, 88 scenes	1 cm/year	Levelling measurements	Courrières, Billy-Montigny, Lens, Cite Saint Paul
Mines Domaniales de Potasse d'Alsace, France [14]	Underground potash mining	1995-2000 2004-2010 2015-2018	InSAR PSI SBAS	ERS ENVISAT Sentinel-1	Up to 8.4 cm/year when mine still open	Levelling measurements	Staffelfelden village, Bollwiller and Pulversheim
Upper Silesian Coal Basin, Poland 21]	Coal mining	1992-1995	InSAR	ERS-1/2	2.5 cm/month		Katowice
NW of Upper Silesian Coal Basin, Poland [22,45,58]	Coal mining	1995-2000	InSAR	ERS	10-20 cm/year		Bytom
		1992-2003	PSInSAR	ERS-1 ENVISAT	Correlation between ground subsidence and mining seismicity		
		Jul 2011- Jun 2012	SqueeSAR DInSAR	TerraSAR-X	7 mm/year	Geodetic data	
Wieliczka Salt Mine, Poland [26]	Salt mining	1992-2000	DInSAR PSI	ERS-1/2	Up to 2.5 cm/year	Levelling campaigns	Wieliczka
Rudna, Poland [27]	Cooper mine- mining induced seismicity	Nov 2016-Dec 2016	DInSAR	Sentinel-1	Up to 9 cm in a month		Tarnowek village
Rydułtowy Mine, Poland [28]	Underground coal mining, active mine	Jan 2017-Nov 2018	DInSAR SBAS	Sentinel-1A	Up to 1 m	Levelling data	Rydułtowy town
Legnica-Glogow Copper Belt, Poland [46,73]	Cooper mine, active mine	2019-2020	PSI	Sentinel 1A	Up to 5 cm/year		Glogow, Lubin, Polkowice
		Jan 1994-March 1994 1999-2001	DInSAR	ERS-1/2	Up to 24 cm		
Inowrocław Salt Dome, Poland [47]	Salt mining, Solno mine closed in 1991	1993-1998	PSI	ERS-1/2	4 mm/year subsidence Up to 8 mm/year uplift	Precise levelling GPS surveys	Inowrocław
Campine Coal Basin, Belgium [16]	Coal mining, post mining monitoring	1991-2005 2003-2010 2011-2014 2014-2022	PSI	ERS-1/2 ENVISAT COSMO-SkyMed Sentinel-1A	12 mm/year subsidence Up to 18 mm/year uplift	GNSS Levelling	Hasselt, Beringen, and Genk

Mining area	Type of mine	Monitoring period	SAR technique	Radar satellite data	Deformation rate	Other monitoring method used	Urban areas
Ruhr region, Germany [33]	Coal mining, Active and abandoned mines	2003-2009 Feb 2008-Apr 2008 Jun 2007-Ian2008	DInSAR PSI	ENVISAT TerraSAR-X ALOS	Up to 40 cm in 253 days	Levelling GPS survey	More urban centres from the region
South Limburg, Netherlands [50]	Coal mining, closed since 1974, dewatering measures until 1994 in Julia mine	2015-2019	PSI	Sentinel-1	Up to 2.5 mm/year uplift		Heerlen Geleen Brunssum
Athens Basin, Greece [51]	Old mining activity	1992-2002	PSI	ERS-1/2	1-2 mm/year		Athens
La Union mining area, Spain [59,60,2]	Silver and lead abandoned open pit	1998-2000 2003-2004 2003-2008	CPT (A-DInSAR)	ERS ENVISAT	Up to 3 cm/year	Field survey Aerial-photo interpretation	La Union
Cardona salt mines, Spain [48]	Salt mine	1992-2010 2010-2015 2015-2019	PSI	ERS ENVISAT Cosmo-SkyMed Sentinel-1	Both subsidence- up to 15 mm/year and uplift- up to 20 mm/year	GNSS monitoring High-precision levelling	Cardona
Karvina, Czech Republic [34]	Coal mining	2007-2008	DInSAR	ALOS	Up to 3 cm/year	GPS fast static method	Karvina
South Derbyshire and Leicestershire, UK [62,61]	Coal mining closed since the beginning of 1990s	2003-2009	ISBAS	ENVISAT	10 mm/year uplift		Coalville
Solotvyno Salt Mine, Ukraine [11,12,13]	Salt mining, closed in 2010	1997-2001 2002-2010 2014-2016 2016-2017	SqueeSAR™	ERS Envisat Sentinel-1 Cosmo-SkyMed	3 cm/year		Solotvyno
		2014-2019	SBAS	Sentinel-1	5 cm/year	Comparison with Velasco, 2017	
		1992-2021	PSI SBAS	ERS Envisat Sentinel-1	30 mm/year subsidence		
Ocnele Mari, Romania [35]	Salt mining	Aug- Nov 2010	InSAR DInSAR	RADARSAT-2	2-4 mm/year		Ocnele Mari
Rosia Jiu, Romania [36]	Coal Mining	Jul-Dec 2014	DInSAR PSI	TerraSAR-X	Impact of mining captures		Rosia Jiu
Witbank Coalfields, South Africa [32]	Coal mining, historical mining activity	1995-2008	DInSAR	ERS-1/2	4.7 cm over 105 days		Witbank
Matjhabeng gold mine, South Africa [73]	Gold mine	1998-1999	DInSAR	ERS-2	Up to 11.2 cm	-	Welkom

Mining area	Type of mine	Monitoring period	SAR technique	Radar satellite data	Deformation rate	Other monitoring method used	Urban areas
Xuemiaotan mine, China [20]	Coal Mining	Feb 2019-Aug 2019	SBAS-InSAR D-InSAR Offset-tracking	Sentinel-1A	Up to 3.6 m for monitoting period	GNSS data	Yulin city
BinChang, China [37]	Coal Mining	Jul 2007-Aug 2007	D-InSAR	ALOS PALSAR	Up to 2.6 cm		
Tianjin, China [49]	Coal Mining	1994-2000	PSI QPS-InSAR	ERS	Up to 3 cm/year		Tianjin
Guqiao South Mine, China [38]	Coal Mining	Nov 2017-Dec 2017	DInSAR	Sentinel-1A	Up to 6 cm for monitoring period		Huainan
Twentymile mine, Colorado, U.S.A. [73]	Coal mining	1995-1996	DInSAR	ERS-1/2	Up to 6 cm		Closest urban area at 35 km distance
N4W mine, Carajás Mineral Province, Amazon Region, Brazil [52]	Open pit Iron mining	2012	PSI	TerraSAR-X	Up to 31.2 cm/year		Parauapebas
New South Wales, Australia [29,30]	Underground coal mining, active mine	1993-2005	DInSAR	ERS-1/2 Radarsat-1 JERS-1	2-3 cm		
		2007-2008		ALOS	4.5 cm (Southern coalfield)	GPS field survey	Campbelltown Tahmoor
Southern Coalfield, Australia [31]	Underground coal mining	2007-2011	DInSAR, TS-InSAR	ALOS-1 ENVISAT	Up to 10 cm/year		Wollongong Tahmoor
El Teniente, Chile [39,44,54]	Underground cooper mine and open pit, active mine	2010-2015	PSI & A-DInSAR	COSMO-SkyMed	centimetric motion outside the subsidence crater		Near Rancagua
Surabaya, Indonesia [54]	Coal mine	2014-2017	SBAS	ALOS-2	Up to 2cm/year		Surabaya
Jharia Coalfield, Jharkhand, India [10]	Coal mining	2012	DInSAR	Radarsat-2	Up to 30 cm/year	Precision levelling	Jharia

3.1. Spatial Distribution and types of mines

More than 65% of the studies on monitoring subsidence mining areas by InSAR techniques are focused on sites located in Europe. The European country with the highest number of studies on this topic is Poland, where coal mining [21, 22, 28, 45, 58] salt mining [26, 47] and cooper mining [26, 46, 73] areas are presented. The intensive exploitation in the Upper Silesian Coal Basin crossing Poland is one of the reasons of this large number of studies, as half of the scientific contributions from Poland are on coal mining field. Figure 1 presents the spatial distribution statistics of the scientific contributions using InSAR monitoring for different types of mining subsidence per country. Considering the general overview, more than 55% of the scientific contributions are dedicated to the coal mining subsidence monitoring, spread in 14 of the 19 countries included in this review. Second country as number of scientific contributions on subsidence coal mining monitoring using InSAR techniques is China. However, the number of studies on coal mining for this country is much higher [74-82], but only a few representative studies were considered for the analysis. Next countries as number of studies on coal mining are Australia and U.K.

Studies on salt subsidence mining monitoring using InSAR represents the second mining category as number of contributions, with 16% , followed by cooper (9%), silver and lead -La Union, Spain- 7%, iron (N4W mine, Brazil and Rancourt, Lorraine, France) 4.5%, followed by the more special types of mining, potassium (France) and gold (South Africa), with one scientific contribution each. In the subsidence study from Athens Basin, Greece, the type of mining is not specified [51].

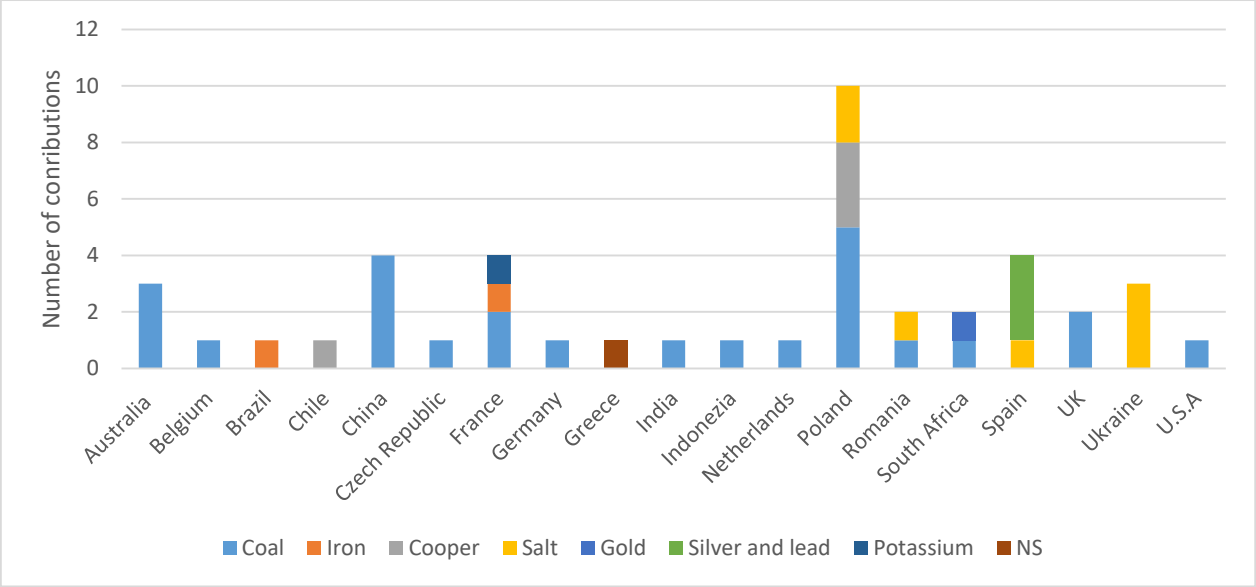

Figure 1. Spatial Distribution of the scientific contributions using InSAR monitoring for different types of mining subsidence per country

Considering the exploitation mode, some of the scientific contributions refers to underground mining [14,16,24,25,28,35,46], or open pit [36,39,52,59,60]. Meanwhile, there are some mining areas where both underground and open pit exploitation are found, e.g.El Teniente, Chile [39,44].

Looking on the status of mining activities, some of the scientific contributions present the consequences in terms of mining subsidence for:

- historical sites (e.g. iron mining in Rancourt, Lorraine, France [43], coal mining in Witbank Coalfields, South Africa [32], Athens Basin [51], South Limburg, Netherlands [50],
- closed mines in the 1990s (e.g.Inowroclaw, Poland [47], South Derbyshire and Leicestershire, UK [62], Nord/Pas-e-Calais, France [25], Ocnele Mari, Romania [35], Campine Coal Basin, Belgium [16]),
- closed mines after 2000 (e.g. salt mine in Poland [11-13]),
- active mining sites (e.g. coal mine in Gardanne France [24], Rydultowy, Poland [28], Legnica Glogow Cooper Belt, Poland [46], New South Wales Australia coal mine [29,30], El Teniente, Chile [39,44], China [20,37,38,49])
- mining sites with historical and active mines (e.g. Ruhr region, Germany [33])

3.2. Temporal Distribution of scientific contributions

As mentioned in the introduction, articles on subsidence mining monitoring using InSAR techniques have a temporal evolution starting from 1999 [21] to 2023 [16]. Figure 2 presents all the temporal resolution, considering the country where the monitored site areas are found. Most articles are written in 2016 and 2020 (5 articles each), followed by 2011, 2015 and 2021 when 4 articles per each year are available. Until 2010 only an article deals with mining subsidence in a site outside Europe [29]. This can be associated with the history of mining areas and the subsidence problems associated with the mining activities, including for the human settlements located in the mining areas. For some large mining centres, more scientific contributions are available at different time intervals, as subsidence mining monitoring is necessary for preventing accidents and also for urban planning. Thus, for Upper Silesian Coal Basin, 4 scientific contributions are available for 1999 [21], 2003 [22], 2011 [45], 2015 [58] with radar satellite data covering monitoring periods from 1992 to 2012.

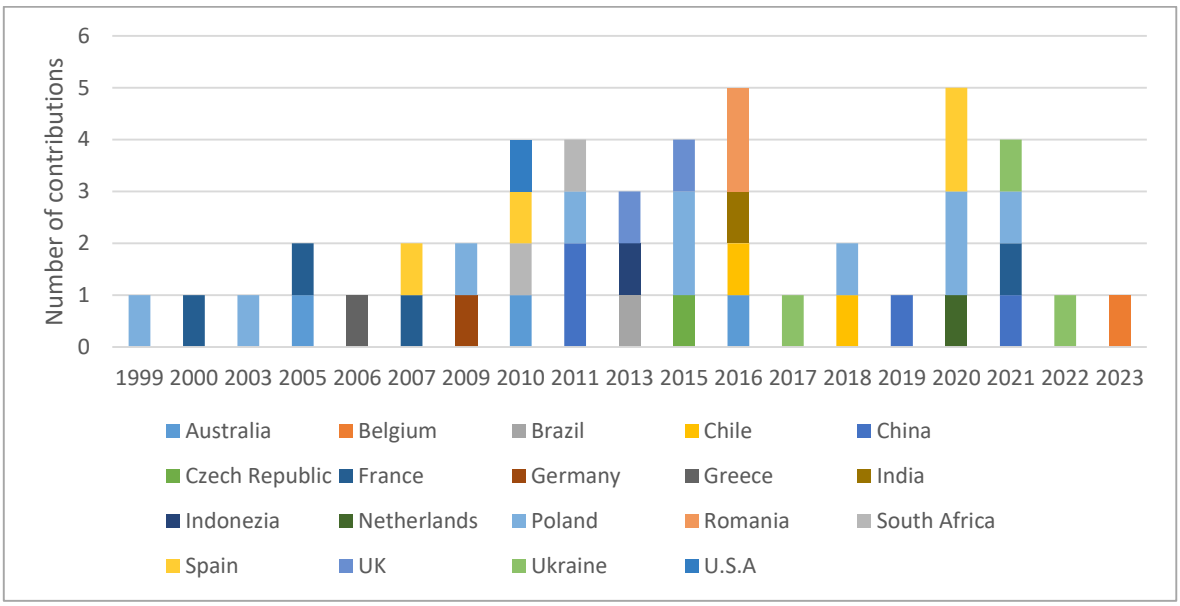

Figure 2. Temporal Distribution of the scientific contributions using InSAR monitoring for subsidence mining per country

3.3. Temporal evolution of SAR techniques and of radar satellite missions revealed by scientific contributions

The evolution of SAR techniques can be observed in the temporal distribution of articles. Hence, for the articles published until 2003, the classical InSAR and DInSAR techniques are used for subsidence monitoring. At the same time, ERS-1 and ERS-2 satellite data are used. As next steps, the PSI technique is introduced in the mining subsidence monitoring in France [43], and the CPT A-DInSAR technique is used for La Union mining area, Spain [60]. Data from Radarsat-1 and JERS-1 radar satellite missions are used since 2005 [29], from ENVISAT, TerraSAR-X and ALOS-1 since 2009 [33]. The QPS-InSAR technique appears in 2011 in [49], and in 2013 the SBAS technique is used for the the radar data from ALOS-2 satellite mission for subsidence monitoring in Surabaya, Indonesia [54]. Same year, the ISBAS technique is used for monitoring mining subsidence in South Derbyshire, U.K [62]. Unless available since 2011, SqueeSAR technique is used only in 2015 for the NW of the Upper Silesian Coal Basin [58]. Meanwhile, in 2016, the data from RADARSAT-2 mission is used in [35] and [10], while Cosmo-SkyMed and Sentinel-1 data is used in [11]. Recent scientific works are using the most advanced InSAR techniques applied on temporal series of satellite missions from ERS-1 to Sentinel-1.

Most scientific contributions from this review used more than one satellite data set and more than one SAR technique for mining subsidence monitoring. Figure 3 presents the number of data sets from each SAR mission and the number of the scientific contributions in which each SAR monitoring technique was used. Considering the SAR monitoring techniques, as the scientific contributions generally are using more than one SAR technique for mining subsidence monitoring, the SAR techniques from the different categories described in section 2 were used 54 times. The most used SAR technique is DInSAR (used 20 times), followed by PSI (17 times), SBAS (7 times) and SqueeSAR (3 times), the rest of the methods being used only in one or two scientific contributions. The first three techniques are also the most used techniques used in combination when more than one approach is considered for a scientific contribution. This combination can be used as validation method of the results when no other alternative method is available.

Looking on SAR missions, 61 data sets were used, with scientific contributions where data sets from 3 or 4 SAR mission were used in the same study. This approach is mainly used for widening the monitoring time interval. Therefore, from the 61 data sets, 21 data sets are from the ERS-1&2 missions, 12 data sets from the Sentinel-1 mission, 10 data sets from ENVISAT mission, 6 data sets from ALOS mission, 4 data sets from TerraSAR-X and Cosmo-SkyMed missions, 3 data sets from RADARSAT, and 1 JERS data set. These values show at a first sight the free and open access for the European SAR missions ERS-1&2, Sentinel-1 and ENVISAT. Europe had a quasi-permanent SAR mission in orbit, since 1991, the gap being between the retirement of ENVISAT-ASAR mission in 2012, and the launch of Sentinel 1 mission in 2014. For this time interval, the monitoring time series were filled with data from Cosmo-SkyMed or TerraSAR-X missions.

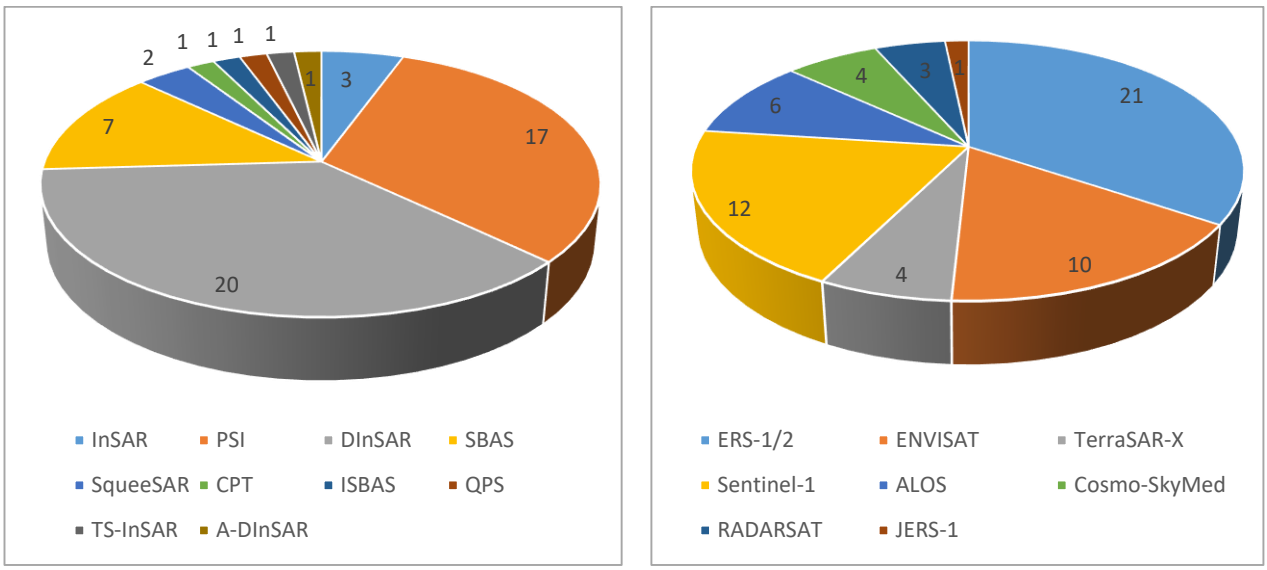

Figure 3. (a) Number of different SAR monitoring techniques used in the scientific contributions; (b) Number of data sets from different SAR missions in the scientific contributions

3.4. Deformation rates and alternative mining subsidence monitoring methods

Maximum vertical deformation rate in the monitored sites has different values from a few millimetres (e.g. Athens Basin [51], Ocnele Mari, Romania[35], South Limburg, Netherlands [50], Inowrocław, Poland [47]), to centimetres (e.g. La Union, Spain [59,60], Cardona Salt mine, Spain [48], Karvina mine, Czech Republic [34], Solotvyno, Ukraine [11,12], Roncourt, France [43]), tens of centimetres (e.g. NW of Upper Silesian Coal Basin [22], Matjhabeng gold mine South Africa [73], N4W iron mine, Brazil [52]), and even meters (e.g. Rydułtowy Mine, Poland [28]) considering the particularities of each mining monitored area.

The vertical deformation can be materialized in the field as subsidence (negative displacement) or as uplift (positive displacement), considering the conservation measures for the closed fields of different mining exploitations. There might be cases when in the same mining area both subsidence and uplift are present, e.g. Cardona Salt Mine, Spain [48].

For 17 of the studied mining sites, alternative monitoring methods are available for validation and for a more complete overview. This is also useful for a clear view of historical subsidence lasting for more than 30 years back, as InSAR monitoring is available only from 1990s. Figure 4 presents a statistic of the alternative monitoring methods used for subsidence monitoring of the mining sites included in the review. For 12 of the 17 studies, the precise levelling was used as alternative subsidence monitoring method, followed by 7 studies where GNSS surveys were also used. In 4 of these studies, the precise levelling was used in combination with the GNSS field surveys. For one study the validation method was also SAR monitoring [12], from a study conducted on the same area, with data from the same SAR satellite mission and the same time interval [11]. For another study, the precise levelling was used as alternative method, in combination with the aerial photo interpretation [59].

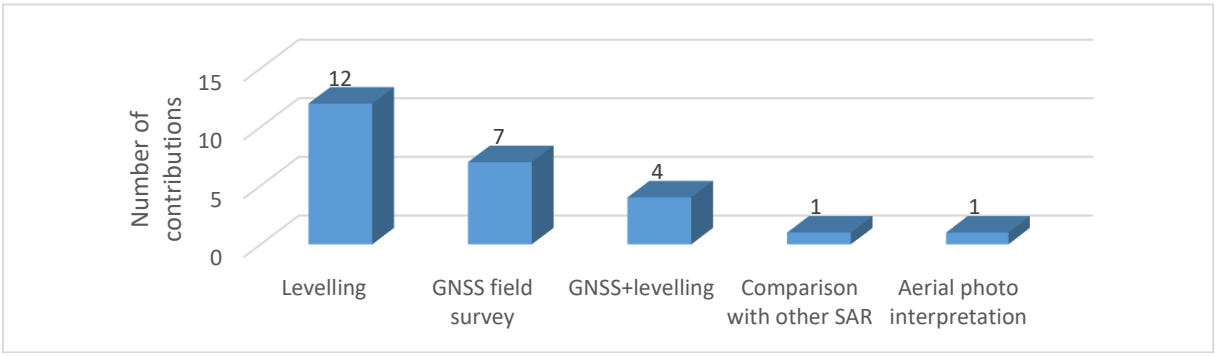

Figure 4. Alternative methods for subsidence monitoring of the mining sites included in the review

The relatively low number of scientific contributions in which alternative subsidence monitoring methods are used is justified by the disadvantages of the traditional monitoring methods, such as the expensive cost and the low extent [25].

3.5. Urban areas affected by mining subsidence. Study case on Ocnele Mari

Many of the cities located in mining areas encountered subsidence problems due to the mining exploitation activities. Considering the time interval in which mining activities took place, sometimes the urban area are affected during exploitation period and in other cases after the closure of the works. Looking on the consulted scientific contributions, Roncourt, France is one of the affected cities, a fast evolving subsidence inducing severe damages to houses in February 1999 [43], four years after the last iron mine was closed down in Lorraine [83]. The subsidence was perfectly captured by the SAR monitoring, showing the usefulness of this methods for preventive monitoring.

For Cite Saint Paul, France a city placed in a coal mining area, different displacements were observed. From analyses, it was established that the main cause of subsidence was mining activity and neotectonics [25].

The intensive coal mining in the Upper Silesian Coal Basin in Poland, in the industrial era [84], led to the appearance of major subsidence problems in cities like Bytom. The cumulated displacements affected here between July and August 2011 the Karb urban area, and those were responsible for the demolition of 28 buildings [58].

For the Wieliczka Salt Mine, Poland, the PSI subsidence monitoring technique revealed the existence of subsidence in the Wieliczka urban area, field investigations confirming the visible damage [26].

Another city affected by salt mining exploitation is Solotvyno, Ukraine, where the permanent instabilities evidenced by InSAR monitoring are confirmed by building damages [13].

In many cases, for the urban mining areas, either active, historical or under conservation, the continuous monitoring is necessary in order to avoid further damages to the human settlements. Major reforms of mine closure, varied from region to region, going through a number of serious issues, from high unemployment that follows industrial restructuring to labour migration. This is not the case on Australian mainland, where mining activities change the demographics, with populations moving from regions which don't have mining exploitation to places where can take advantage of mining employment, the influx of migrants being represented by single males. Dynamic economic activities reveal the lower unemployment and higher workforce participation in mining regions compared to non-mining regions [85]. As for the urban centres from the mining areas in Australia, an advantage is their positioning outside the exploitation area, considering also the large wild area available on this continent. Following the same emigration trend, mining is part of modern South Africa [86]. Discoveries of diamonds and gold in 1886 generated massive immigration, urbanisation, capital investment and labour migration. Further discoveries of coal, manganese, iron ore and platinum metals enable the industry of mining to be the basis for industrial revolution that develop Africa into an economic power, through empowering agriculture, services, urbanization and infrastructure [86].

On the other side, since the beginning of socio-economic changes in Central and South-Eastern Europe, pointing on two periods, from 1988 to 1989 and 2010 to 2011, most countries of this part of Europe had a descending population trend [87], caused by emigration, negative demographic natural movement, high unemployment and labour migration as a consequence of industrial restructuring. Remarkable examples are from Germany, where jobs in coal mining decreased from 80.000 to 8000 between 1990 to 2000, due to increasing mechanization and rationalization, and the case of Romania, where in the period 1990 – 2018, the employee decreased from 55.000 to less than 5000, due to the diminishing of coal production and usage [88]. From the consulted scientific contributions, Bytom city in Poland [84], or Karvina city in Czech Republic [89], La Union in Spain [90] are some examples of collapsed urban mining areas.

According to Sageata, R. [91], the coal decreasing activity in Romania, has resulted in unemployment, and local communities (in Jiu valley micro-region) has been looking for new development alternatives such as the exploitation of the tourist heritage. Major employers in the micro-region are active in electricity, heat, mining and textile industry, water-sewage infrastructure. Closure of mining perimeters in the Jiu Valley generated a cascade effect regarding unemployment, depopulation, decrease in population incomes, quality of life and local budget incomes. The total population of Jiu Valley decreased from 167.456 in 1990 to 120.734 inhabitants in 2018, while the mining activities contribution had the same significant decline, from 76% in 1990 to 1.71% in 2018 [88]. Furthermore, a decreasing trend is registered to the mining perimeters in operation, the active preparation factories, consequence on the low production and the investment sector. Rosia-Jiu village, situated in the Jiu Valley is one of the active open pit mines affected by subsidence. The human settlements are located at distances of 100-150 m from the opencast, leading to the danger of building's damages due to subsidence [92]. This issue reinforces the necessity of continuous mining subsidence monitoring for some mining areas, especially in urban environment.

Case Study on Ocnele Mari

As in the examples above, Ocnele Mari is an urban mining area affected by effects of the salt exploitation works. Teica Mare old mine was closed in the 1990s, after a major collapse in Field II, close to a densely populated area [68]. Its exploitation was followed by crashes in 2001 and 2005 with devastating impacts on human settlements and pollution on Sarat River [93]. It included the destruction of a large part of the urban infrastructure, such as the connection road from Ocnele Mari to the neighboring settlements, the electric network, the water supply network [66], and of several tens of individual houses [68]. The SAR monitoring from the area confirmed the continuous displacements in the area [35]. As a consequence of the collapses, crashes, and also of the mining activities reduction in the area, the population dynamics suffered different variations during the study period (1992-2020). Demographic analyses carried out in this study and their results are presented below.

The demographic research starts from the incursion into the hypothesis of a mining activity which, according to Mancini [68], is likely to attract workers from other regions causing migration flows and changes in the local demographic trends. Furthermore, a gender imbalance could appear due to the predominance of male workers. A potential growth of the population could be perceived as a positive consequence of the mining activity, which facilitate jobs long term maintenance.

The reestablishment process of the Romanian mining sector started in 1997 and consisted of mine closures and massive layoffs of people working in the extractive industry. Furthermore, after Romania's adherence to the EU in 2007, 550 mines were closed and around 370 towns and villages were socially and economically affected [94]. However, the old mine was closed in Ocnele Mari since 1992 as specified in section 2.2. Figure 5 presents the evolution of population size in Ocnele Mari from 1992 to 2022. Thus, since 1992, the number of population has gradually decreased until 2022, recording the lowest value in 2000 with 3432 persons. After 2005, the total population increased again, followed by a decrease after 2015. Mine closure impacts the economy and the employment opportunities, the social and economic development.

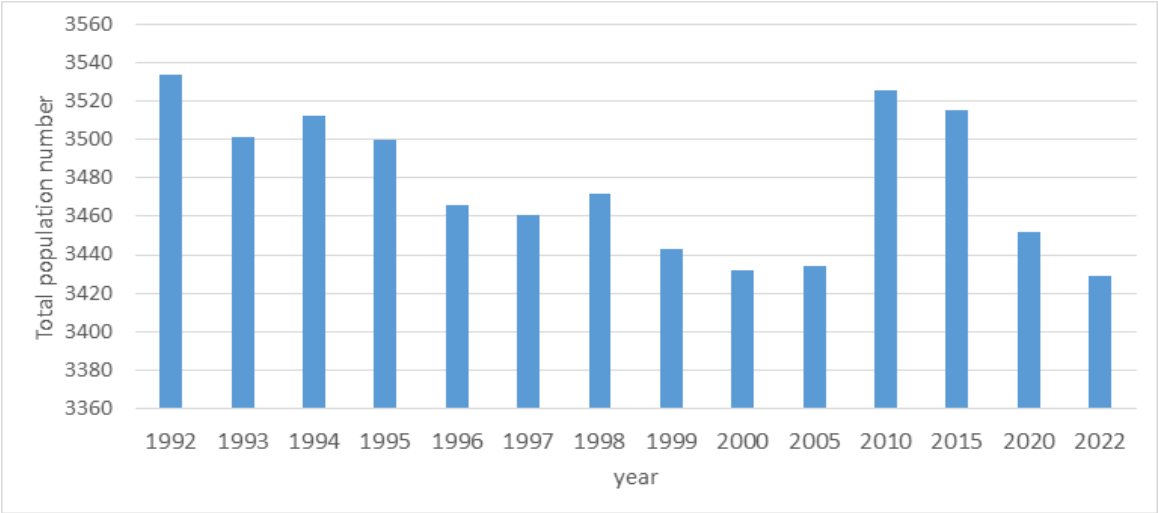

Figure 5. Population size in Ocnele Mari during 1992 to 2022. Data source: INSSE, TEMPO

Population decline is the partial process of the mining activity closure of the social and economic development thus this demographic phenomenon is highlighted by the small or negative rates regarding birth and population natural increase, as presented in Figure 6. Migration is one important factor of population change in addition to fertility and mortality [95]. Regardless of a birth deficit, as it can be seen in the present study case, embodied as an effect of more deaths than births, population can either grow or reduce in size depending on migration rates. Migration effect influence population dynamics highly controlled by the negative natural increase rate, during all temporal series, excepting the positive rates in 2022, due to higher birth rate than the death rate.

Since 1992, the dynamics of the population in Ocnele Mari proves negative values, with the highest value in 1999 (Figure 7), determined by the high number of deaths and population departures. In 2020 and 2022 the dynamic trend changed with positive values, as the number of births increased, while the number of deaths and immigrants were lower. One possible explaining for the population increasing trend in 2020 and 2022 is the massive return of the population in the home country, from abroad, as a result of Coronavirus pandemic.

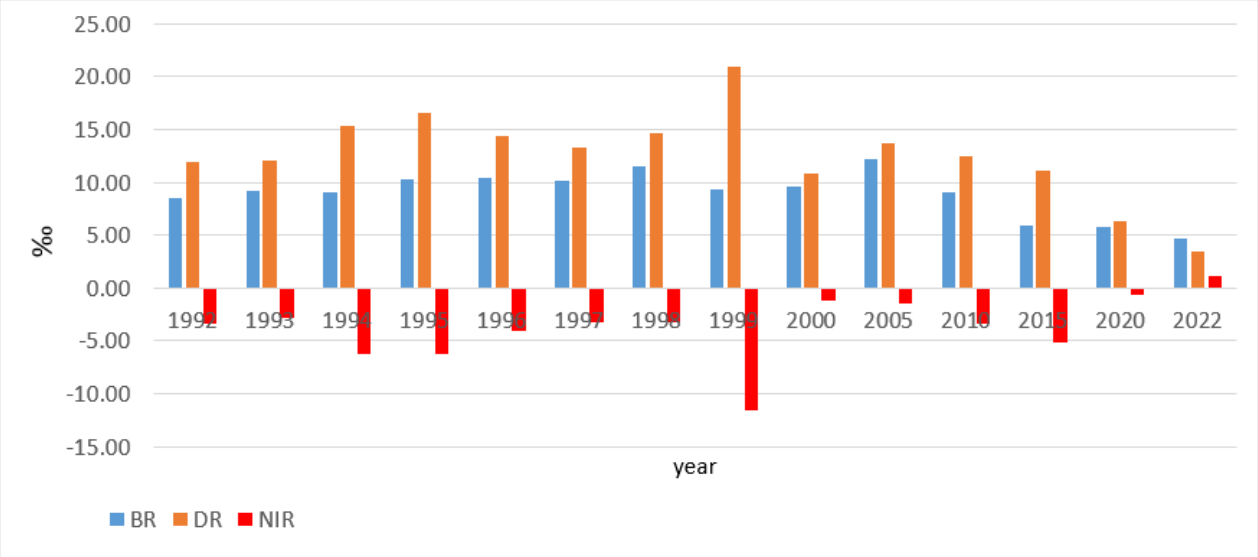

Figure 6. Natural increase rate in Ocnele Mari during 1992 to 2002. Natural increase rate is the result of the difference between birth rate and death rate. *Data source: INSSE, TEMPO*

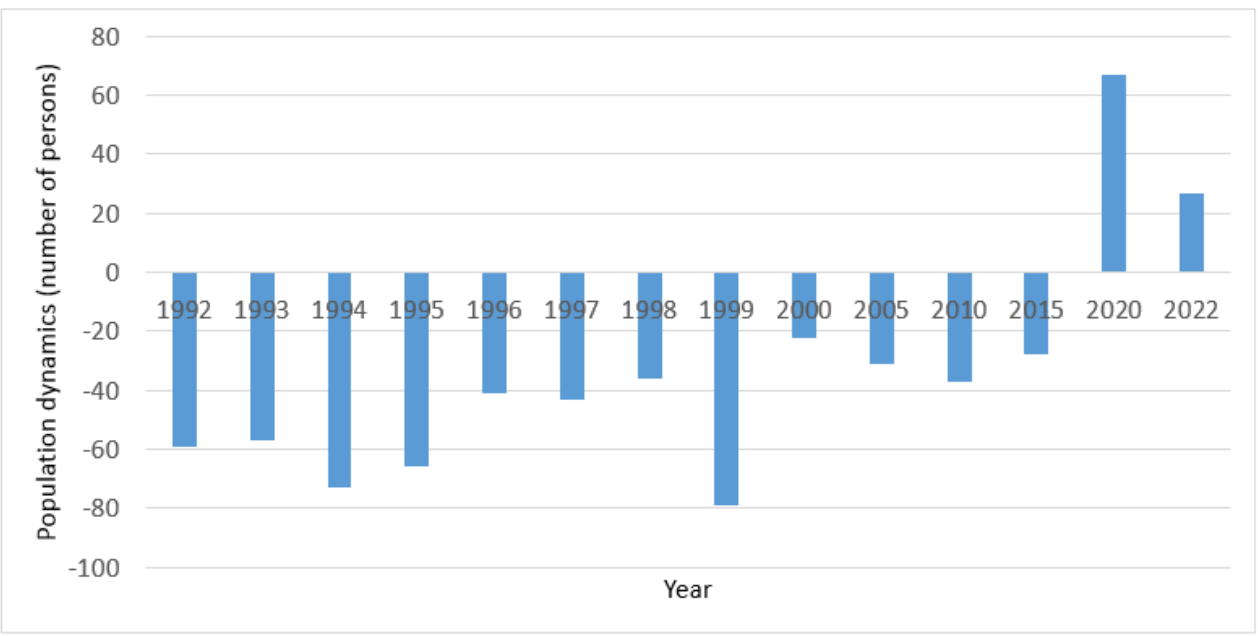

Figure 7. Total population dynamics in Ocnele Mari during 1992 – 2022. The total population dynamics is the sum of the following variables: the difference between number of birth and number of deaths, together with the difference between the number of immigrants and emigrants. *Data source: INSSE, TEMPO*

The demographic analysis in Ocnele Mari from 1992 to 2022, reflected by population dynamics and natural increase rate does not pursue the Mancini [65] hypothesis, which foresees possible population growth due to mining industry in the region and the possibility of social and economic development. In Ocnele Mari the situation is totally different, as the analysed time series shows an evident population decline (Figure 7) determined by the mine collapsing events, putting forward the social and political instability after 1989, when Romania turned from a socialist republic to a democratic country. As a consequence, at national level, most of the mines were considered cost-damaging, thus, the mining industry experienced restructuring processes, while the population have had to sustain their living conditions through different new form and places of living.

4. Discussions

Several tens of study cases on mining subsidence monitoring using InSAR techniques were presented in this paper. These techniques are applied successfully for underground and open pits, for active, under conservation or historical mines, considering both large areas (such as Upper Silesian Coal Basin) and smaller areas, such as urban areas (Roncourt, France). The scientific contributions cover analyses made for mines exploiting several types of minerals, by using different SAR data, different InSAR techniques, validated with other in-situ deformation monitoring methods, when available. SAR datasets encloses data starting with the first radar missions ERS-1 and ERS-2 and reaching up the acquisitions of the current SAR sensors (such as Sentinel-1). The free and open access to the European SAR missions (ERS-1&2, ENVISAT and Sentinel-1) could be revealed by the large number of scientific contributions using data from these missions. SAR data allowed revealing deformations of milimetric and centimetric level. Higher levels of deformations were registered for study areas where mining activities occurred for a long period of time and exploitation was made without considering the sustainable development. In many of these cases, the deformations led to damages on urban infrastructures. This can be one of the factors influencing the immigration of population from those areas, besides the reduction of mining activities, or even closing the mining works. On the other side, for mining sites with urban centers outside the influence area and without exploitations constraints (e.g. Australia), the population dynamics consists in emigration of population.

Ocnele Mari is one of the urban areas affected by the socio-economic changes in South-Eastern Europe from the 1990s, when many mining sites were closed. This could be revealed by the analyses of the demographic indicators showing the population decline.

5. Conclusions

Urban subsidence resulted from mining activities is a encountered phenomena worldwide. In the last three decades InSAR techniques brought new elements in the estimation and interpretation of displacements generated by mining activities, by investigating their effects on ground surface. In many cases, for the urban mining areas, the continuous monitoring is necessary in order to avoid further damages to the human settlements. InSAR techniques are suitable for this type of monitoring, considering the temporal and spatial resolution of SAR satellites nowadays. At the same time, it is worth emphasizing the continuous evolution and refinement process of InSAR techniques which allow an effective monitoring. As any monitoring method, InSAR techniques have their limitations. Therefore, in some cases it is useful the use of InSAR techniques for complementing the in-situ subsidence monitoring methods, such as precise levelling. Ocnele Mari study case revealed the consequences of the mining overexploitation and of the lack of monitoring and instruments to be used when a mining area is closed. Continuous monitoring might be an instrument for sustainable development of urban mining areas, either located in active or closed mining sites, allowing decision making for urban planning and revitalization of mining areas.

References

[1] **Del Prete S., Parise M.,** 2013
An overview of the geological and morphological constraints in the excavation of artificial cavities, Filippi M., Bosák P. (Eds), 2013. Proceedings of the 16th International Congress of Speleology, July 21–28, Brno. Volume 2: 236–241. Czech Speleological Society. Praha

[2] **Schuchova K., Lenart J.,** 2020
Geomorphology of old and abandoned underground mines: Review and future challenges, Progress in Physical Geography: Earth and Environment, 44(6), 791–813, https://doi.org/10.1177/0309133320917314

[3] **Chen M., Tomas R, Li Z., Motagh M., Li T., Hu L., Gong H., Li X., Yu J., Gong X.** 2016
Imaging Land Subsidence Induced by Groundwater Extraction in Beijing (China) Using Satellite Radar Interferometry, Remote Sens. 2016, 8(6), 468, https://doi.org/10.3390/rs8060468

[4] **Wang L., Teng C., Jiang K., Jiang C., Zhu S.** 2022
D-InSAR Monitoring Method of Mining Subsidence Based on Boltzmannand Its Application in Building Mining Damage Assessment, KSCE Journal of Civil Engineering (2022) 26(1):353-370

[5] **Karila K., Karjalainen M., Hyyppä J., Koskinen J., Saaranen V., Rouhiainen P.** 2013
A Comparison of Precise Leveling and Persistent Scatterer SAR Interferometry for Building Subsidence Rate Measurement, ISPRS Int. J. Geo-Inf., 2, 797-816. doi: 10.3390/ijgi2030797

[6] **Raucoules D., Colesanti C., Carnec C.** 2007
Use of SAR interferometry for detecting and assessing ground subsidence, C. R. Geoscience 339 (2007) 289–302. https://doi.org/10.1016/j.crte.2007.02.002

[7] **Galloway D.L., Burbey T.L.** 2011
Review: Regional land subsidence accompanying groundwater extraction, Hydrogeology Journal, 19, 1459-1486. doi:10.1007/s10040-011-0775-5

[8] **Radutu A., Gogu R.C.** 2018
Chronological reflection on monitoring urban areas subsidence due to groundwater extraction, In E3S Web of Conferences, Volume 85, Proceedings of the EENVIRO 2018 Conference: Sustainable Solutions for Energy and Environment, Cluj Napoca, Romania, 9–13 October 2018;

[9] **Del Soldato M., Confuorto P., Bianchini S., Sbarra P., Casagli N.** 2021
Review of Works Combining GNSS and InSAR in Europe, Remote Sens. 2021, 13, 1684. https://doi.org/10.3390/rs13091684

[10] **Chatterjee R.S., Singh K.B., Thapa S., Kumar D.** 2016
The present status of subsiding land vulnerable to roof collapse in the Jharia Coalfield, India, as obtained from shorter temporal baseline C-band DInSAR by smaller spatial subset unwrapped phase profiling, International Journal of Remote Sensing, 37:1, 176-190, DOI: 10.1080/2150704X.2015.1126376

[11] **Velasco V., Sanchez C., Papoutsis I., Antoniadi S., Kontoes C., Aifantopoulou D., Paralykidis S.** 2017
Ground deformation mapping and monitoring of salt mines using InSAR technology. SMRI Fall 2017 Technical Conference 25–26 September 2017 Münster, Germany, 1–20, 2017.

[12] **Szűcs E., Gönczy S., Bozsó I., Bányai L., Szucs L., Szakacs A., Szárnya C., Wesztergom V.** 2021
Evolution of surface deformation related to salt-extraction-caused sinkholes in Solotvyno (Ukraine) revealed by Sentinel-1 radar interferometry. Nat. Hazards Earth Syst. Sci., 21, 977–993, 2021. https://doi.org/10.5194/nhess-21-977-2021.

[13] **Dobos E., Kovács I.P., Kovács D.M., Ronczyk L., Szucs P., Perger L., Mikita V.** 2022
Deformation Monitoring and Risk Mapping in the Surroundings of the Solotvyno Salt Mine (Ukraine) between 1992 and 2021. Sustainability 2022, 14, 7531. https://doi.org/10.3390/su14137531.

[14] **Modeste G., Doubre C., Masson F.** 2021
Time evolution of mining-related residual subsidence monitored over a 24-year period using InSAR in southern Alsace, France, International Journal of Applied Earth Observation and Geoinformation, 2021, 102, pp.102392, DOI:10.1016/j.jag.2021.102392

[15] **Bamler R., Hartl P.** 1998
Synthetic aperture radar interferometry. Inverse Problems, 14, R1–R54.

[16] **Declercq P.-Y., Dusar M., Pirard E., Verbeurgt J., Choopani A., Devleeschouwer X.** 2023
Post Mining Ground Deformations Transition Related to Coal Mines Closure in the Campine Coal Basin, Belgium, Evidenced by Three Decades of MT-InSAR Data, Remote Sens. 2023, 15, 725. https://doi.org/10.3390/rs15030725

[17] **Stow R., Wright P.** 1997
Mining subsidence Land Surveying by SAR Interferometry, 3rd ERS Symp., Florence, Italy. https://earth.esa.int/eogateway/documents/20142/37627/3rd-ERS-Symposium-Space-at-the-Service-of-our-Environment.pdf

[18] **Ferretti A., Monti-Guarnieri A., Prati C., Rocca F., Massonnet D.** 2007
InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation, (TM-19, February 2007). ESA Publications

[19] **Chelbi S., Khireddine A., Charles J.** 2011
Interferometry process for satellite images SAR. ELECO 2011 7th International Conference on Electrical and Electronics Engineering, 1-4 December, (pg. 180-184). Bursa, TURKEY.

[20] **Ma J., Yang J., Zhu Z., Cao H., Li S., Du X.** 2022
Decision-making fusion of InSAR technology and offset tracking to study the deformation of large gradients in mining areas-Xuemiaotan mine as an example., Front. Earth Sci. 10:962362, doi: 10.3389/feart.2022.962362

[21] **Perski A., Takeuchi W., Aoki Y.** 1999
ERS SAR interferometry for land subsidence detection in coal mining areas, Corrigendum to EOQ 63, pages 25-29.

[22] **Perski Z., Jura D.** 2003
Identification and measurement of mining subsidence with SAR Interferometry: potentials and limitations, Proceedings, 11th FIG Symposium on Deformation Measurements, Santorini, Greece, 2003.

[23] **Wasowski J., Bovenga F.** 2014
Investigating landslides and unstable slopes with satellite Multi Temporal Interferometry: Current issues and future perspectives, Engineering Geology, 174, 103-138. Preluat de pe http://dx.doi.org/10.1016/j.enggeo.2014.03.003

[24] **Carnec C., Delacoyrt C.** 2000
Three years of mining subsidence monitored by SAR interferometry, near Gardanne, France, Journal of Applied Geophysics 2000, 43(1): p.43-54

[25] **Gueguen Y., Deffontaines B., Al Heib M., Fruneau B., De Michele M., Raucolues D., Guise Y., Planchenault J.** 2007
Detection and characterisation of residual mining subsidence using DInSAR and PS interferometry: application to Nord/Pas-De-Calais coalbasin (Northern France), Envisat Symposium 2007, Apr 2007, Montreux, Switzerland. pp.NC

[26] **Perski Z., Hanssen R., Wojcik A., Wojciechowski T.** 2009
InSAR analyses of terrain deformation near the Wieliczka Salt Mine, Poland, Engineering Geology 106 (2009) 58–67, DOI:10.1016/j.enggeo.2009.02.014

[27] **Malinowska A., Witkowski W., Guzy A., Hejmanowski R.** 2018
Mapping ground movements caused by mining-induced earthquakes applying satellite radar interferometry, Engineering Geology 246 (2018) 402–411, https://doi.org/10.1016/j.enggeo.2018.10.013

[28] **Pawluszek-Filipiak K., Borkowski A.** 2020
Integration of DInSAR and SBAS Techniques to Determine Mining-Related Deformations Using Sentinel-1 Data: The Case Study of Rydułtowy Mine in Poland, Remote Sens. 2020, 12, 242; doi: 10.3390/rs12020242

[29] **Chang H-C., Ge L., Rizos C.** 2005
DInSAR for mine subsidence monitoring using multi-source satellite SAR images, Proceedings. 2005 IEEE International Geoscience and Remote Sensing Symposium. IGARSS '05 Seoul, Korea (South), 2005, pp. 1742-1745, doi: 10.1109/IGARSS.2005.1526339.

[30] **Ng A. H-M., Ge L., Yan Y, Li X., Chang H-C., Zhang K., Rizos C.** 2010
Mapping accumulated mine subsidence using small stack of SAR differential interferograms in the Southern coalfield of New South Wales, Australia, Engineering Geology 115 (2010) 1–15, https://doi.org/10.1016/j.enggeo.2010.07.004.

[31] **Du Z., Ge L., Li X., Ng A.** 2016
Subsidence Monitoring over the Southern Coalfield, Australia Using both L-Band and C-Band SAR Time Series Analysis, Remote Sens. 2016, 8, 543; doi:10.3390/rs8070543

[32] **Engelbrecht J., Inggs M.R.** 2011
Detection and monitoring of surface subsidence associated with mining activities in the Witbank Coalfields, South Africa, using differential radar interferometry, 2011 IEEE International Geoscience and Remote Sensing Symposium, Vancouver, BC, Canada, 2011, pp. 1596-1599, doi: 10.1109/IGARSS.2011.6049452.

[33] **Walter D., Wegmüller U., Spreckels V., Hannemann W., Busch W.** 2009
Interferometric Monitoring of an Active Underground Mining Field with High-Resolution SAR Sensors. ISPRS Archives – Volume XXXVIII-1-4-7/W5, 2009. https://www.isprs.org/proceedings/xxxviii/1_4_7-W5/paper/Walter-168.pdf.

[34] **Kadlečík P., Kajzar V., Nekvasilová Z., Wegmüller U., Doležalová H.** 2015
Evaluation of the subsidence based on dInSAR and GPS measurements near Karviná, Czech Republic, AUC Geographica, 50, No. 1, pp. 51–61, http://dx.doi.org/10.14712/23361980.2015.86

[35] **Poenaru V., Badea A., Cimpeanu S.M., Dana Negula I**. 2015
Synthetic Aperture Radar for Assessing Land Degradation in a Salt Mining Area – Ocnele Mari Case-Study, Rev. Roum. Géogr./Rom. Journ. Geogr., 59, (2), p. 117–127, 2015, Bucureşti.

[36] **Poenaru V.D., Dana Negula I., Badea A., Cuculici R.** 2016
Environmental Impact Assessment of Rosia Jiu Opencast Area Using an Integrated SAR Analysis, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLI-B8, 2016, XXIII ISPRS Congress, 12–19 July 2016, Prague, Czech Republic

[37] **Gong Y.** 2011
Mining Subsidence Monitoring Using ALOS Satellite Data, 2011 19th International Conference on Geoinformatics, Shanghai, China, 2011, pp. 1-3, doi: 10.1109/GeoInformatics.2011.5981107.

[38] **Jiang C., Wang L., Yu X., Wei T., Chi S., Guo Q.** 2021
Prediction of 3D deformation due to large gradient mining subsidence based on InSAR and constraints of IDPIM model, International Journal of Remote Sensing, 42:1, 208-239, doi: 10.1080/01431161.2020.1804088.

[39] **Falorni G., Del Conte S., Bellotti F., Colombo D.** 2018
InSAR monitoring of subsidence induced by underground mining operations, in Y Potvin & J Jakubec (eds), Caving 2018: Proceedings of the Fourth International Symposium on Block and Sublevel Caving, Australian Centre for Geomechanics, Perth, pp. 705-712

[40] **Crosetto M., Monserrat O., Cuevas-Gonzales M., Devanthery N., Crippa B.** 2016
Persistent Scatter Interferometry: A Review. ISPRS Journal of Photogrammetry and Remote Sensing, 115, 78 https://doi.org/10.1016/j.isprsjprs.2015.10.011

[41] **Ferretti A., Prati C., Rocca F.** 2001
Permanent Scatterers in SAR Interferometry. IEEE Transactions On Geoscience And Remote Sensing, 39(1), 8-20.

[42] **Bell J. W., Amelung F., Ferretti A., Bianchi M., Novali F.** 2008.
Permanent scatterer InSAR reveals seasonal and long-term aquifer-system response to groundwater pumping and artificial recharge. WATER RESOURCES RESEARCH, 44(2). doi:10.1029/2007WR006152

[43] **Colesanti C., Le Mouelic S., Bennani M., Raucoules D., Carnec C., Ferretti,A.** 2005
Detection of mining related ground instabilities using the Permanent Scatterers technique—a case study in the east of France, International Journal of Remote Sensing, 26:1,201 — 207, DOI: 10.1080/0143116042000274069

[44] **Sanchez F., Conde A., Salva B., Colombo D.** 2016
Use of SAR radar satellite data to measure ground deformation in underground and open pit mine sites, El Teniente case study, Chile, APSSIM 2016 – PM Dight (ed.), Australian Centre for Geomechanics, Perth, ISBN 978-0-9924810-5-6.

[45] **Mirek K., Mirek J.** 2011
Correlation between Ground Subsidence and Induced Mining Seismicity, Upper Silesia Coal Basin Case Study, Polish Journal of Environmental Studies, 20 (4A). pp. 253-257.

[46] **Bugajska N.J., Milczarek W.J.** 2021
Remote sensing monitoring of influence of underground mining in the area of the S3 Express Road, IOP Conf. Ser.: Earth Environ. Sci. 684 012028. DOI 10.1088/1755-1315/684/1/012028

[47] **Szczerbowski Z., Piątkowska A.** 2015
Towards Data Integration and Analysis in the Detection of Terrain Surface Deformation in the Case of the Inowrocław Salt Dome, Geomatics and Environmental Engineering, Volume 9, Number 4, 2015. DOI dx.doi.org/10.7494/geom.2015.9.4.85

[48] **Rodriguez-Lloveras X., Puig-Polo C., Lantada N., Gili J.A., Marturia J.** 2020
Two decades of GPS/GNSS and DInSAR monitoring of Cardona salt mines (NE of Spain)–natural and mining-induced mechanisms and processes, Proc. IAHS, 382, 167–172, 2020. https://doi.org/10.5194/piahs-382-167-2020

[49] **Perissin D., Wang T.** 2011
Time-Series InSAR Applications Over Urban Areas in China, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 4, no. 1, pp. 92-100, March 2011, doi: 10.1109/JSTARS.2010.2046883.

[50] **Bruna M.** 2020
Analyzing subsidence in the Netherlands with attribute-enriched InSAR data, Master Thesis, Delft University of Technology, http://resolver.tudelft.nl/uuid:90970051-1c2c-4bfa-8862-051c4cdf3b5a.

[51] **Parcharidis Is., Lagios S., Sakkas V., Raucoules D., Feurer D., Le Mouelic S., King C., Carnec C., Novali F., Ferretti A., Capes R., Cooksley G.** 2006
Subsidence monitoring within the Athens Basin (Greece) using space radar interferometric techniques, Earth Planets Space, 58, 505–513, 2006.

[52] **Hartwig M.E., Paradella W.R., Mura J.C.** 2013
Detection and Monitoring of Surface Motions in Active Open Pit Iron Mine in the Amazon Region, Using Persistent Scatterer Interferometry with TerraSAR-X Satellite Data. Remote Sens. 2013, 5, 4719-4734; doi:10.3390/rs5094719

[53] **Berardino P., Fornaro G., Lanari R.** 2002
A New Algorithm for Surface Deformation Monitoring Based on Small Baseline Differential SAR Interferograms. IEEE Transactions On Geoscience And Remote Sensing, 40(11), 2375-2383. doi:10.1109/TGRS.2002.803792

[54] **Aditiya A., Takeuchi W., Aoki Y.** 2017
Land Subsidence Monitoring by InSAR Time Series Technique Derived From ALOS-2 PALSAR-2 over Surabaya City, Indonesia, IOP Conf. Ser.: Earth Environ. Sci. 98 012010, DOI 10.1088/1755-1315/98/1/012010.

[55] **Ferretti A., Fumagalli A., Novali F., Prati C., Rocca F., Rucci A.** 2011
A New Algorithm for Processing Interferometric Data-Stacks: SqueeSAR. IEEE Transactions on Geoscience and Remote Sensing, 49(9), 3460-3470. doi:10.1109/TGRS.2011.2124465

[56] **Even M., Schulz K.** 2018
InSAR Deformation Analysis with Distributed Scatterers: A Review Complemented by New Advances. Remote Sens. 2018, 10, 744. https://doi.org/10.3390/rs10050744

[57] **Bitelli G., Bonsignore F., Pellegrino I., Vittuari L.** 2015
Evolution of the techniques for subsidence monitoring at regional scale: the case of Emilia-Romagna region (Italy). 372, pg. 315-321. Copernicus Publications on behalf of the International Association of Hydrological Sciences. doi:10.5194/piahs-372-315-2015

[58] **Przyłucka M., Herrera G., Graniczny M., Colombo D., Béjar-Pizarro M.** 2015
Combination of Conventional and Advanced DInSAR to Monitor Very Fast Mining Subsidence with TerraSAR-X Data: Bytom City (Poland), Remote Sens. 2015, 7, 5300-5328; doi:10.3390/rs70505300.

[59] **Herrera G., Tomas R., Vicente F., Lopez-Sanchez J.M., Mallorqui J.J., Mulas J.** 2010
Mapping ground movements in open pit mining areas using differential SAR interferometry, International Journal of Rock Mechanics & Mining Sciences 47 (2010) 1114–1125, doi:10.1016/j.ijrmms.2010.07.006

[60] **Herrera G., Tomas R., Lopez-Sanchez J.M., Delgado J., Mulas J., Mallorqui J.J, Duque S., Mulas J.** 2007
Advanced DInSAR analysis on mining areas: La Union case study (Murcia, SE Spain), Engineering Geology, Volume 90, Issues 3–4, 27 March 2007, Pages 148-159, https://doi.org/10.1016/j.enggeo.2007.01.001

[61] **Bateson L., Cigna F., Boon D., Andrew S.** 2015
The application of the Intermitent SBAS (ISBAS) InSAR method to the South Wales Coalfield, UK, International Journal of Applied Earth Observation and Geoinformation 34 (2015) 249–257. https://doi.org/10.1016/j.jag.2014.08.018

[62] **Sowter A., Bateson L., Strange P., Ambrose K., Fifik Syafiudin M.** 2013
DInSAR estimation of land motion using intermittent coherence with application to the South Derbyshire and Leicestershire coalfields, Remote Sensing Letters, 4:10, 979-987, DOI: 10.1080/2150704X.2013.823673.

[63] **Perissin D., Wang T.** 2012
Repeat-Pass SAR Interferometry With Partially Coherent Targets, IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 50, NO. 1, JANUARY 2012

[64] **Raderschall L., Springare L.-S.** 2019
Enhancing WELL-BEING in mining regions: key issues and lessons for developing indicators, 3rd OECD meeting preconference,
https://www.oecd.org/cfe/regionaldevelopment/Wellbeing_MiningRegions_3rdOECDMeeting_PreConference.pdf

[65] **Mancini L., Sala S.** 2018
Social impact assessment in the mining sector: Review and comparison of indicators frameworks, Resources Policy 57, 98-111. https://doi.org/10.1016/j.resourpol.2018.02.002

[66] **Popa L., Porcutan A.** 2010
The Impact of Salt Exploitation over Ocnele Mari Dwelling, Vâlcea Departament, Geographica Timisiensis, vol. 19, nr. 1, 2010 (pp. 395-400)

[67] **Balteanu D., Enciu P., Deak G.** 2006
A large scale collapse in the Ocnele Mari salt mine field, Getic Subcarpathians, Romania, Studia Geomorfologica Carpatho – Balcanica, XL, 119 – 126.

[68] **Trifu C-I., Shumila V.** 2010
Microseismic Monitoring of a Controlled Collapse in Field II at Ocnele Mari, Romania, Pure Appl. Geophys. 167 (2010), 27–42, DOI 10.1007/s00024-009-0013-4

[69] **Mesescu A.A.** 2011
The Ocnele Mari salt mine collapsing sinkhole – a natech breakdown in the Romanian sub – Carpathians, Carpathian Journal of Earth and Environmental Sciences, Vol. 6, No. 1, p. 215 – 220

[70] **Societatea Nationala a Sarii.** 2012
Sucursala Ramnicu Valcea, Salina Ocnele Mari, https://www.salrom.ro/ocnele-mari-c.php

[71] **National Institute of Statistics in Romania.** 2023
http://statistici.insse.ro:tempo-online/

[72] **Gueguen Y., Deffontaines B., Fruneau B., Al Heib M., De Michele M., Raucolues D., Guise Y., Planchenault J.** 2007
Monitoring residual mining subsidence of Nord/Pas-de-Calais coal basin from differential and Persistent Scatterer Interferometry (Northern France), Journal of Applied Geophysics 69 (2009) 24–34. doi:10.1016/j.jappgeo.2009.02.008

[73] **Eneva M.** 2010
Detection of Surface Deformation at Mining and Geothermal Sites Using Satellite Radar Interferometry (InSAR), Paper presented at the 44th U.S. Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, Salt Lake City, Utah, June 2010

[74] **Yang Z.F., Li J., Zhu J., Feng G.C., Wang Q.J., Hu J., Wang C.** 2017
Deriving Time-series Three-dimensional Displacements of Mining Areas from a Single-geometry InSAR Dataset, Journal of Geodesy. doi:10.1007/s00190-017-1079-x.

[75] **Yang Z.F., Li Z.W., Zhu J.J., Hu J., Wang Y.J., Chen G.L.** 2016
InSAR-Based Model Parameter Estimation of Probability Integral Method and Its Application for Predicting Mining-Induced Horizontal and Vertical Displacements, IEEE Transactions on Geoscience and Remote Sensing 54(8): 4818–4832. doi:10.1109/tgrs.2016.2551779.

[76] **Yang Z.F., Li Z.W, Zhu J.J., Preusse A., Hu J., Feng G.C., Papst M.** 2018
Time-Series 3-D Mining-Induced Large Displacement Modeling and Robust Estimation from a Single-Geometry SAR Amplitude Data Set, IEEE Transactions on Geoscience and Remote Sensing 56 (6): 3600–3610. doi:10.1109/tgrs.2018.2802919.

[77] **Zhang Y.H., Wu H.A., Kang Y.H., Zhu C.G.** 2016
Ground Subsidence in the Beijing-tianjinhebei Region from 1992 to 2014 Revealed by Multiple Sar Stacks, Remote Sensing 8 (8): 675. doi:10.3390/rs8080675.

[78] **Zhao C.Y., Lu Z., Zhang Q.** 2013
Time-series Deformation Monitoring over Mining Regions with SAR Intensity-based Offset Measurements, Remote Sensing Letters4, no. 5: 436–445. doi:10.1080/2150704X.2012.746482.

[79] **Wang Z., Yu S., Tao Q., Liu G., Hao H., Wang K., Zhou C.** 2017
A Method of Monitoring Three-dimensional Ground Displacement in Mining Areas by Integrating Multiple InSAR Methods, International Journal of Remote Sensing 39 (4): 1199–1219. doi:10.1080/01431161.2017.1399473.

[80] **Chen D., Chen H., Zhang W., Cao C., Zhu K., Yuan X.** 2020
Characteristics of the residual surface deformation of multiple abandoned mined-out areas based on a field investigation and SBAS-InSAR: A case study in Jilin, China. Remote Sens. 12, 3752. doi:10.3390/rs12223752

[81] **Wang L.Y., Deng K.Z., Zheng M.N.** 2019
Research on ground deformation monitoring method in mining areas using the probability integral model fusion D-InSAR, sub-band InSAR and offset-tracking. Int. J. Appl. Earth Obs. Geoinf. 2019, 85, 101981.

[82] **Chen Y., Yu S., Tao Q., Liu G., Wang L., Wang F. et al.** 2021
Accuracy verification and correction of D-InSAR and SBAS-InSAR in monitoring mining surface subsidence, Remote Sens. 13, 4365. doi:10.3390/rs13214365

[83] **Didier C., Leloup J.** 2006
The French Experience of Post Mining Management, AB Fourie & M Tibbett (eds), Mine Closure 2006: Proceedings of the First International Seminar on Mine Closure, Australian Centre for Geomechanics, Perth, pp. 199-210, https://doi.org/10.36487/ACG_repo/605_12

[84] **Kantor-Pietraga I.** 2021
Does One Decade of Urban Policy for the Shrinking City Make Visible Progress in Urban Re Urbanization? A Case Study of Bytom, Poland, Sustainability 2021, 13, 4408. https://doi.org/ 10.3390/su13084408

[85] **Kotey B.** 2014.
Demographic and economic impact of mining on remote communities in Australia, in Resources Policy, Volume 42, December 2014, Pages 65-72, https://doi.org/10.1016/j.resourpol.2014.10.005

[86] **Cole M., Broadhurst J.** 2020
Mapping and classification of mining host communities: A case study of South Africa, The Extractive Industries and Society Volume 7, Issue 3, July 2020, Pages 954-964, https://doi.org/10.1016/j.exis.2020.06.007.

[87] **Rechlowicz M., Tkocz M.** 2013
Depopulation of traditional mining regions in Central and East Europe: case study of the upper-Silesian Basin (Poland) and the Donetsk Basin (Ukraine), Proceedings of the 1st Annual International Interdisciplinary Conference, AIIC, Azores, Portugal.

[88] **BSERC** 2019
Report on the current role of coal mining and related policies in the TRACER target regions, Project no: 836819 – Smart strategies for the transition in coal intensive regions. https://tracer-h2020.eu/wp-content/uploads/2019/11/TRACER-D3.1_Report_final.pdf

[89] **Sery O., Svobodova H., Silhan Z., Szczyrba Z.** 2018
Shrinking of Cities in the Czech Republic and its Reflection on Society: Case Study of Karviná City, Geographica Pannonica, Volume 22, Issue 1, 68–80 (March 2018), DOI: 10.5937/22-16622

[90] **Martínez-López S., Martínez-Sánchez M.J., Pérez-Sirvent C.** 2021
Do Old Mining Areas Represent an Environmental Problem and Health Risk? A Critical Discussion through a Particular Case, Minerals 2021, 11, 594. https://doi.org/10.3390/min11060594

[91] **Sageata R.** 2010
Geografia urbana. Editura Universitatii "Lucian Blaga", Sibiu, ISBN 978-606-12-0009-2

[92] **Poenaru V., Popescu A., Patrascu C., Cuculici R.** 2015
Assessment of Rosia Jiu Mining Area through Terrasar-X New Imaging Modes, In Proceedings of FRINGE'15: Advances in the Science and Applications of SAR Interferometry and Sentinel-1 InSAR Workshop, Frascati, Italy, 23-27 March 2015, Ouwehand L., Ed., ESA Publication SP-731. doi:10.5270/Fringe2015.291

[93] **Poenaru V., Badea A., Savin E.** 2012
Assessment of the Ocnele Mari Salt Mine Exploitation Impacts on the Vegetation Coverage Using Multispectral Remote Sensing Data, AgroLife Scientific Journal - Volume 1, 2012, CD-ROM ISSN 2285-5726; ISSN-L 2285-5718

[94] **Botezan C., Constantin V., Meltzer M., Radovici A., Pop A., Alexandrescu F., Stefanescu L.** 2020
Is There Sustainable Development after Mining? A Case Study of Three Mining Areas in the Apuseni Region (Romania), Sustainability 2020, 12, 9791; doi:10.3390/su12239791

[95] **Lutz W., Gailey N.** 2020
Depopulation as a Policy Challenge in the Context of Global Demographic Trends, UNDP Serbia, Editor: Megan Niedermeyer, ISBN 978-86-7728-292-9

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