SIRIMA

SINKHOLE HAZARD AND RISK MANAGEMENT IN POST MINING AREAS

RFCS PROJECT NO 101157400

Co-funded by the European Union

Deliverable D.1.1

Comprehensive overview of the SIRIMA Project

WP.1. Project management and coordination

Responsible Partner**:** Główny Instytut Górnictwa – Państwowy Instytut Badawczy, Poland

Contributing Partners:

1. Institit National de L'Evironnement Industriel et des Risques - INERIS, France
2. Bureau de recherches géologiques et minière - BRGM, France
3. DMT-Gesellschaft fur Lehre und Bildung mbH - THGA, Germany
4. Instytut Mechaniki Górotworu Polskiej Akademii Nauk – IMG PAN, Poland
5. Systra Subterra Ingenieria SL, Spain
6. Université de Lorraine, France

Authors: : Siwek S., Kotyrba A., Vuidart I., Vieille J., Niedbalska K., Moellerherm S., Garcia B., Mehdizadeh R., Tajduś K.

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1. Introduction

Document Overview

The SIRIMA: *Sinkhole Hazard and Risk Management in Post-Mining Areas* project is carried out with co-financing from the Research Found for Coal and Steel of the European Union as the action RFCS-2023-01-RPJ Coal Research Projects under Grant Agreement No. 101157400.

This document entitled "Comprehensive overview of the SIRIMA Project", represents the deliverable for Task 1.3 and is denoted as D.1.1. The purpose is to prepare an overall project review, which could be used as a reference basis for monitoring project's results on every stage of its implementation. The following sections of this review contain:

- Summary (Section 1)
- Description of the project subject (Section 2, 3)
- Objectives of the Project (Section 4)
- Detailed description of WPs (Section 5)
- Conclusions (Section 6)
- References (Section 7)

Contributing Partners

The SIRIMA Project Consortium consists of seven Partners and one Associated Partner. The table below presents the Consortium participants along with the contact details of the persons responsible for the implementation of the SIRIMA project in their home institutions:

Partner	Full Name	Contact Person	Contact Email
GIG-PIB	Główny Instytut Górnictwa - Państwowy Instytut Badawczy	Sławomir Siwek	ssiwek@gig.eu
INERIS	Institut national de l'environnement industriel et des risques	Isabelle Vuidart	Isabelle.VUIDART@ineris.fr
BRGM	Bureau de recherches géologiques et minières	Pascal Dominique	p.dominique@brgm.fr
DMT	DMT-Gesellschaft fur Lehre und Bildung mbH - THGA	Tobias Rudolph	tobias.rudolph@thga.de
IMG-PAN	Instytut Mechaniki Górotworu - Polskiej Akademii Nauk	Krzysztof Tajduś	tajdus@imgpan.pl
SUBTERRA	Systra Subterra Ingenieria SLU	Beatriz Garcia Bernabeu	bgarcia2@systra.com
UL	Université De Lorraine	Rasool Mehdizadeh	rasool.mehdizadeh@univ-lorraine.fr
GEODERIS	GEODERIS	Pascal Bigarre	pascal.bigarre@geoderis.fr

Table 1 Contact list of persons responsible for the implementation of the SIRIMA project at the Consortium Partners

General Information about Project

Figure 1 Graphical presentation of the Partners in the SIRIMA project.

The SIRIMA project focuses on increasing knowledge and experience related to the threats of post-mining areas in EU Member States. The main objective of the project is to reduce the occurrence of uncontrolled and unexpected movements of the Earth's surface in the areas of shallow abandoned coal mines. These movements, apart from subsidence related to the conducted mining or movements resulting from the impact of mining tremors, can also take the form of uplifts caused by the lifting of the groundwater table in the rock mass and sudden, discontinuous deformations of the ground surface, i.e. sinkholes. The sinkhole hazard is the main type of hazard affecting coal regions in transition. It is due to shallow mining works and the resulting risk of damage to the buildings, infrastructure or threat to people in post-mining areas.

2. State of art

The management of post-mining areas in the European Union countries is an important issue for safety and economic reasons. The adopted European Green Deal policy will, over the next 20-30 years, intensify problems resulting from the closure of hard coal mines. In addition to the closure of hard coal or metal ore mines and the introduction of a zero-emission economy throughout the European Union, it is important to manage water resources and counteract the threat of sinkholes. This is directly related to the ongoing climate change. After the closure of underground mines, due to economic reasons it is necessary to restore the hydrogeological conditions which existed before mining in as many post-mining areas as possible. This process increases the risk of sinkholes.

Closure of an underground operating mine, whether it is hard coal or metal ores, is associated with increased threats to the safe use of the surface of these areas. These threats include: gas emissions, seismic tremors, continuous surface deformations (subsidences and uplifts) and discontinuous deformations (sinkholes). Continuous deformations may take the form of subsidences and uplifts and cover large areas of the terrain. Subsidence usually occurs during deep mining and within a specified time frame (usually up to 5 years) (Dudek et al. 2022; Tajduś et al. 2021; Kwiatek 1998). In the longer term, and also after the cessation of rock mass drainage, a partially reverse process may occur, i.e. uplift of the terrain (Tajduś et al. 2023, Kotyrba 2023). In the areas where subsidence has occurred before, the occurrence of reverse process, on a scale many times smaller than the original subsidence, usually due to the applied protections, should not affect the development and infrastructure of the post-mining area. The situation will be different in areas of former, shallow mining exploitation, where discontinuous surface deformations in the form of sinkholes are frequently observed.

Mining excavations (roadways, galleries, shafts) and exploitation voids (rooms, adits etc) left in the rock mass, in the case of a closed mine, are nothing more than empty spaces (voids) filled with gas (air) or water. The left voids have various spatial shapes, from simple to very complex. A rise in the groundwater table or heavy rainfall cause changes in the properties of the rock that has been in dry state over the years. When the rock mass in dry state the main factors causing underground voids to collapse are rainfall waters infiltrating the rock and dynamic or static loads (e.g. caused by seismic waves from mining tremors or earthquakes, vibrations generated by machines or rock engineering devices). In such cases the voids start migrating from the exploitation level or caving levels to the surface and finally form a sinkhole. When the rock is re-saturated with water after the mine is closed, water becomes the main factor determining the stability of the rock mass with the voids left and their possibility to migrate to the surface. The sinkhole threat exists in every area where there are voids in the geological strata regardless of whether they have a natural or anthropogenic cause. In coal, metal and other mines, sinkholes are observed in the areas with the shallowest drifts and chamber workings (horizontal) as well as in the areas of abandoned mine shafts (vertical).

Sinkholes can be hazardous to human life and property due to its tendency to occur without warning (Singh et al. 1997; Lei 1998; Papadopoulou-Vrynioti 2013). Due to the use of different techniques for mining minerals, the physical and mechanical properties of rocks and the size of the voids left in the rock mass there can't be set the general limit determining from what depth, the void can reach the surface. Based on observed events, it is assumed that sinkholes in the Upper Silesian Coal Basin (USCB) in Poland up occur for shallow mining operations in layered coal deposits (thickness 1-9 m) to a depth of 100 m (Kotyrba 2005), most often for a depth of less than 50 m. In other mining regions in Europe and overseas, the sinkholes can be caused by much deeper mining voids (Didier et al 2005). The main reasons for their occurrence are: the method of mining, the shape of mining body, in layered deposits the number of layers as well as the depth of exploitation, the thickness of the deposit, the presence of geological disturbances, in situ stresses, surface topography, the nature of the overburden, and the solubility of rocks. A change in water conditions causes stress imbalance in the rock mass, a change in the properties of the rock transformed (weakening) by mining activity and thus accelerate the process of sinkhole development. This applies both to situations in which drainage of the rock mass is still maintained (eg. USCB in Poland, Gardanne in France, North Rhine Westphalia in Germany, Ostrava-Karvina in Czech Republic) or where due to natural conditions it was possible to stop the rock mass drainage.

The SIRIMA project, as already mentioned, aims to reduce the occurrence and effects of sinkhole hazards and to develop methods and tools for assessing the risk associated with the possibility of their occurrence. This translates into the safety of use of post-mining areas by their inhabitants, who, after a long period after the mine closure are not aware of the hazards occurring in such areas.

Within the framework of the Research Fund for Coal and Steel in the European Union, many projects have been implemented that address the issue of mine liquidation and the occurrence of post-mining hazards. Projects implemented so far have concerned issues related to mine waters, their quality and possibilities of reuse (WATERCHEM, FLOMINET, MANAGER, LoCAL). Other projects focus on research on the behaviour of mine shafts in various conditions (MISSTER for shafts in active mines, STAMS for shafts in abandoned mines in flooding conditions). There are also projects on research and risk assessment and limiting the impact of abandoned mines on the ground surface (COMEX, MERIDA, TEXMIN, i2MON, TRIM4POSTMINING, REVIRIS, POSTMINQUAKE and POMHAZ – still ongoing). In terms of the subject of the tasks implemented, POMHAZ and POSTMINQUAKE are closest to SIRIMA. The POSTMINQUAKE project focused on post-mining hazards resulting from the possibility of seismic tremors in an abandoned and flooded mine. In some cases, these tremors can cause the reactivation of sinkhole processes or damage to objects on the ground surface. The

SIRIMA project will build on some elements of POSTMINQUAKE (completed on December 31, 2023), including its results and the established monitoring infrastructure (seismic and hydrological sites). In the SIRIMA project, we will try to analyse the hazard of induced seismicity related to the occurrence of sinkholes. The second project, POMHAZ (ongoing), focuses on the interaction and analysis of multiple hazards that may occur in the post-mining area, and the sinkhole hazard is one of the post-mining hazards. The POMHAZ project aims to describe post-mining hazards, including a list of hazards, the interaction between them, and the development of a Decision Support System (DSS) and GIS for post-mining hazards. In cooperation with POMHAZ TEAM we will try to use the same terminology and description of the sinkhole hazard in post-mining areas.

In practice, each of the above-mentioned projects has a task/tasks or, as part of some partial study, that is related to the assessment of the sinkhole hazard associated with shallow mining excavations. However, the sinkhole hazard is only one of the elements taken into account to solve the broader problem of post-mining issues. The presented analyses are limited, they lack comprehensive short-term and long-term risk management, focusing on the risk of loss of surface stability due to sinkholes in post-mining areas that are being restored to their original environmental condition (including the restoration of the groundwater table).

3. Objectives of the SIRIMA project

The main objectives of the project are:

- The creation of an European database of sinkhole and the analysis of the conditions of the occurrence of the sinkholes to better manage the hazard in the future by the coal regions in transition.
- Study the impact of mine flooding on surface instability.
- Identification of sinkhole hazards and risks related to shallow coal mine works.
- Developing a machine learning model to help the different post-mining actors to better predict the sinkhole hazard. This new tool could be very useful for the hazard assesements based on geological, mining and environmental data.
- Proposing an operation monitoring tool, integrating the communication of the hazard to public and decision makers.
- Developing an operational guideline for the mining authorities and stakeholders. The objective of the guideline is to better integrate the sinkhole hazards in the risk management and the sustainable development of the coal region in transition.

In the SIRIMA project, by using the knowledge and experience of the research teams involved, we will attempt to systematize the available knowledge on the sinkhole hazard in a limited area of the European Union, in the countries from which the SIRIMA project partners come, as well as conduct new analyses and apply new research methods. The main goal of these activities is to enable, on the basis of the conducted research and its results, the reduction of the occurrence of uncontrolled and unexpected movements of the Earth's surface (sinkholes) in the areas of shallow, closed hard coal mines.

Based on Polish (Kotyrba 2016, Kotyrba 2018, Kotyrba and Siwek 2019, Kotyrba et al. 2016, www.zapadliska.gig.eu) and French (www.bdmvt.fr) experiences, it is planned to create an internet service to disseminate knowledge about sinkholes. In addition to dissemination elements (notes, materials from documents produced in the project), an interactive map will be created showing areas of shallow mining exploitation of hard coal and/or metal ore deposits and sinkholes according to the information collected by project partners from their countries. The example of the zapadliska.gig.eu service, operating in Poland since 2015, shows that in situations of the sinkhole threat, users of the affected areas intensively search for appropriate information. The purpose of creating the service is therefore to indicate the European Union bodies as institutions implementing tasks close to Europeans. Collecting and including additional information is a very time-consuming process. The issue of post-mining hazards, including sinkholes, concerns practically every member state of the European Union. Due to the complexity of the issue, the analyses conducted concern the areas of the countries whose representatives, the Project Partners, participate in its implementation, i.e. France, Germany, Poland and Spain. The expansion of the issue to other European countries and the collection of information on the scope of shallow mining exploitation (including supplementing the data on the sirima.gig.eu website) is planned to be implemented through the proposal to include participation in the scope of a dedicated Work Package in subsequent RFCS project applications. The Work Package will be submitted to the projects in which partners from countries other than those currently in the SIRIMA project will participate.

The SIRIMA project will apply new research methods to determine the risk of sinkholes in post-mining areas and to manage the risk when planning the redevelopment of such areas. Archival data on sinkholes as well as data provided by geophysical and geodetic measurement systems will be used for these purposes. For the goals of the SIRIMA project, 3 test site were selected:

1. Kazimierz-Juliusz (Poland)
2. Siersza (Poland)
3. Thil (France).

An important element of the undertaken activities will be to organize and systematize knowledge on the process of groundwater level rise during mine flooding and the possibility of linking this process with the increase in the sinkhole hazard. As part of the SIRIMA project, a review of the methods used so far to forecast this process in partner countries will be conducted. Natural and technical factors that determine the occurrence of discontinuous deformations in the areas of abandoned mines will be indicated, along with their characteristics and hierarchy. Based on the data available for the Siersza test site and/or Kazimierz Juliusz test site, a temporal and spatial correlation of the occurrence of sinkhole phenomena in the conditions of mine flooding will be performed against the background of the geological structure and technical and mining conditions. Numerical simulations will be performed to estimate the complex response of the terrain surface and its time-space evolution to mechanical and hydro geological phenomena in the rock mass related to mine flooding.

The project will involve numerical simulations using different tools to estimate the risk associated with the formation of sinkholes and the effects that a sinkhole or subsidence of small horizontal dimensions but significant vertical dimensions may cause in the existing technical or construction infrastructure in the post-mining area (Zevgolis et al. 2023, Tajduś et al. 2023, Dudek et al. 2022, Tajduś et al. 2021, Kotyrba et al. 2023, Kwiatek 1998). This work will approximately model the conditions at the Siersza test site for one of the cases. For all of these activities, one of the validation elements will be analyses of satellite images (InSAR), which allow for broader but detailed observation of changes in the ground surface level in areas at risk of sinkhole processes.

The created database of sinkholes for various post-mining areas, together with the results of hydro geological analyses, will be used for work with machine learning (DL) and deep learning (ML) techniques (Bianchini et al. 2022; Amin et al. 2023). The results of this work may allow for estimating the risk of sinkholes in post-mining areas in a simplified and automated manner.

The project will create a spatial Decision Support System (DSS) for the management of the sinkhole risk in European coal basins integrating social and economic aspects. A decision support system is a system of information that supports business or organizational decision-making activities (Newman et al., 2017; Pavloudakis et al. 2009; Hao et al. 2019, Singh & Ghosh 2016). DSSs serve the management, operations and planning levels of an organization (usually mid and higher management) and help people make decisions upon problems that may be rapidly changing and not easily specified in advance - i.e., unstructured and semi-structured decision problems. Decision support systems can be either fully computerized or human-powered, or a combination of both.

Sinkholes create very serious problems due to the absence of any prior warning, so it is necessary to know what preventative measures can be used to control their occurrence. Remedial measures can be precautionary or preventative measures (such as construction of walls, grouting of voids, backfilling and filling of cracks). When these measures are not possible or in complement of these, the utilization of non-structural risk mitigation measures, such as monitoring seems to be a good solution. The development of monitoring and early warning technologies is primordial to investigate mechanisms of sinkhole formation.

As a part of the SIRIMA project, it is planned to continue and develop the monitoring systems already built and to design and build a new monitoring system aimed at recognizing the risk of sinkholes in the area of the abandoned Siersza hard coal mine in Poland. Monitoring in the selected research areas is based on the following elements:

Seismicity monitoring

Seismological observations are one of the best tools for monitoring the state of the geological medium. They allow for the identification of changes in the rock mass before they appear on the surface (Contrucci et al. 2011; Jousset and Rohmer 2021; Kinscher et al. 2015). The literature presents numerous examples of existing surface deformations in flooded areas of closed mines and the associated induced microseismic activity (Ogasawara et al. 2002; Durrheim et al. 2007; Srinivasan et al.2009; Matrullo et al. 2015; Dominique et al. 2022). Seismological observations conducted in Postminquake project aimed to demonstrate that during the mine flooding, low-energy tremors are observed in various areas of the closed mine which have been flooded (Kotyrba et al. 2024). Within SIRIMA, it is planned to start seismological observations in the area of a flooded mine (Siersza test site). In this case, the possibilities of capturing seismic tremors in the area of an active mine (as a trigger of sinkholing process inside the rock mass) will be sought, which could be identified with the migration of void to the ground surface and the occurrence of a sinkhole. Capturing such shocks could be of great importance for predicting the region of sinkhole occurrence.

Monitoring changes in the gravity field

Monitoring changes in the gravity field of the abandoned mine area over time involves performing periodic gravity measurements in a fixed grid of measurement points. This allows for the study of changes occurring in the structure of geological medium subjected to re-saturation and the resulting changes in the rock mass connected with voids movement. Such work carried out as part of the Postminquake project has shown that gravity measurements provide important spatial information on the location of areas where the mass distribution changes in near surface layers are anomalous. In the area of the studied coal mine Kazimierz-Juliusz, most of the tremors occurred in the vicinity of its already flooded part. The reason for the change in the stress state in the rock mass in this area is the effect of the impact of flood waters on the overburden layers (Kotyrba et al. 2024). Observing the slow process of mine flooding and the subsequent changes in the rock mass requires conducting research over a longer period than lasts implementation of a single project. As part of the SIRIMA, we will continue the work undertaken at the Kazimierz Juliusz test site (Postminquake) and we will establish and start research at the Siersza mine. There is a significant difference in the degree of waterlogging of the rock mass between these polygons. For the Kazimierz Juliusz test site, the flooding process is about halfway through, while for the Siersza polygon, groundwater is already near surface and its table has been lowered by pumping as a way to prevent sinkholes. It is assumed that the observations in the area of Siersza mine, which is near completely flooded, can provide new data usable for protection of the Kazimierz Juliusz sinkhole prone regions.

Monitoring water level changes

Automated groundwater monitoring systems are the best solution for collecting large amounts of water level data with minimal time and effort. These systems not only enable monitoring data from remote locations in the real time, but also eliminate any risk of human error in data recording. The recorded data will be collected in a local data centre and stored for processing and analysis.

The SIRIMA project will focus on observing groundwater level changes in two aspects. The first one is the observation of changes in the long-term elevation of the groundwater table during the flooding of a hard coal mine. In Poland, this scenario is being implemented at the Kazimierz Juliusz test site. The deep piezometer P-Porąbka Klimontów (Postminquake equipment) and the deep piezometer P-Jan Kanty/2023 (SIRIMA equipment) will be used. In the second aspect, research will be conducted on the change in the water level in the area highly threatened by sinkhole processes and attempts to link the observed water level fluctuations with the time of sinkhole occurance will be made. For this purpose, equipment manufactured and installed at the Siersza test site will be used. Data collected by this system will be made available to the local authorities in Trzebinia.

Surface monitoring using satellite techniques (InSAR)

Satellite Radar Interferometry InSAR is a remote sensing technique used to obtain information about the displacement/deformation of the Earth's surface between two or more acquisition dates. Depending on the background plan of the satellites' missions, acquisition dates range from days to weeks. For instance, the Copernicus Sentinel 1 mission has a revisit time ranging from 6 to 12 days. The satellite antenna emits pulses of electromagnetic waves with specialized transmitting and receiving devices called Synthetic Aperture Radar (SAR). This technique enables the scanning of the Earth's surface over an area of many thousand square kilometres in few seconds. The SAR date are composed of the amplitude and the phase of the signal. The amplitude is proportional to the backscattering properties of the surface and the humidity content at the surface. During the recording, information about the amplitude and phase of the radar wave backscattered from the Earth's surface is saved as individual complex pixels, with the phase of this signal recorded the time of its arrival back at the receiver.

The interferogram is generated by differencing the SAR phases between two or more satellite acquisitions. An interferogram contains informations about the displacement of the Earth surface.

Periodic subsidence or uplift formed in the time interval between two SAR images are obtained in the coordinate system of the digital terrain map. This result enables the determination of the boundaries (range) of the current threat to the area in which the deformation process takes place or took place in the past. Archived data with SAR images are available since 1991 (ERS – European Remote Sensing Satelllites) and today with the Copernicus Sentinel 1 (European program, funded by EU and piloted by the European Space Agency).

4. Sinkhole hazard induced by underground coal/ore mining in Project Partner's countries

The work carried out within the SIRIMA project concerns 4 European Union countries: Germany, France, Poland and Spain. Below is a brief information on the risk of sinkholes in each of these countries.

Sinkhole hazard in Germany

The state of North Rhine-Westphalia is characterised by intensive mining activities that date back to Roman times and beyond. These activities were focussed on the extraction of a wide variety of mineral resources, but above all on the extraction of ores, hard coal, lignite and salt but also on the extraction of slate, sand, clay and other mineral resources that could be used as building materials or industrial minerals.

Since then, several thousand mines of various sizes have been operated for the underground extraction of mineral resources. The majority of these mines have been ceased due to the exhaustion of the deposits, due to special events (e.g. high water inflows or mine fires) or due to changes in economic conditions (e.g. sales crises, changes in raw material prices). Approximately 50% of the entire state territory is influenced by hard coal, ore and other minerals' extraction. Hard coal mining occurred in the Aachen region South-West of North Rhine Westphalia (NRW,) in the Ruhr area between Duisburg and Dortmund and in Ibbenbueren/Bielefeld (North of NRW). The following figure provides an overview of the areas affected by abandoned mines.

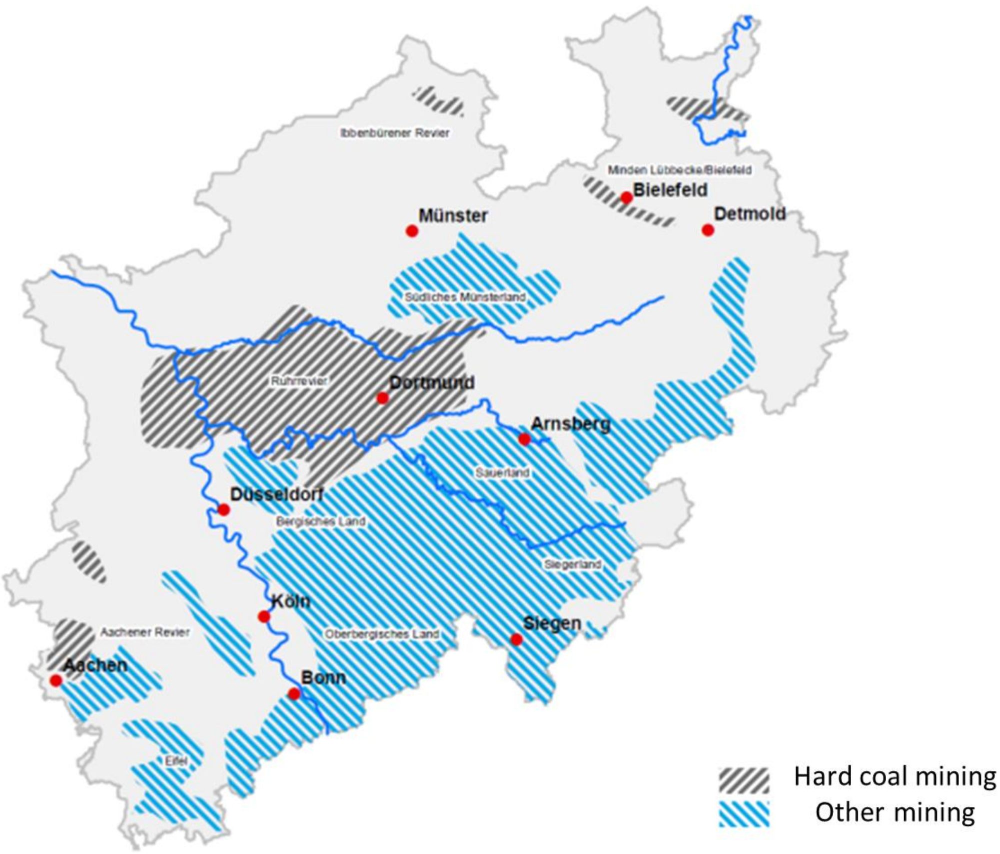


Figure 2 Former mining regions in North Rhine Westphalia

Several major surface collapse events in North Rhine-Westphalia have demonstrated that unsecured or inadequately secured (old, abandoned) mining objects can pose a risk to people and their property. One of these surface collapse events happened at the beginning of January 2000 in a residential area in the Bochum district of Wattenscheid-Höntrop. This event was one of the largest of its kind in the history of the Ruhr region. It is considered particularly spectacular and became known as the Wattenscheid hole or Höntrop crater. Two funnel-shaped, 15-meter-deep shafts collapsed. Luckily, there were no personal injuries.

Figure 3 Sinkhole in a residential area in Bochum (Höntrop crater)

The reason of the surface collapse was the former haulage shaft 4 of the Vereinigte Maria Anna Steinbank colliery in Höntrop, which was shut down in 1905. The Bochumer Verein sold the colliery to Hugo Stinnes, General Director of Deutsch-Luxemburgische Bergwerks und Hütten-AG, who then closed immediately the mine. During the demolition of the surface facilities, the headframe toppled over because it was too-heavy due to the weight of the winding machine and fell headfirst into the shaft, where it became wedged at a depth of 40 metres. The upper part of the shaft, which was 431 metres deep in total, was filled then with more rubble.

Residential buildings were constructed here in the following period. In 1991, the shaft had already been secured with concrete injections. Measurements taken at a depth of 35 m in November 1999 revealed that there were displacements of up to 4 m in the overlying strata.

The crater was 500 m² in size and around 15 metres deep. It took three garages and several cars with it. A second crater of a similar size occurred. The S-Bahn service between Bochum and Essen had to be interrupted due to these collapses. 7500 m³ of concrete were used to backfill the crater. The works costed around 12 Million German Mark (6 Million €). VEBA as the legal successor was responsible for the remediation which lasted 7 years in total.

According to experts, the event was one of the largest one-day collapses in the history of the Ruhr region. This fact has forced the state of North Rhine-Westphalia to set up a risk management system for mining legacies that are prone to ground movements and sinkholes. Shortly afterwards, an exploratory programme was launched.

In North Rhine-Westphalia, the mining authority is responsible for measures to avert dangers from abandoned mine workings that are no longer subject to the mining supervision in accordance with Section 48 (3) of the regulatory agency law NRW (OBG NRW). This means that the applicability of this law is linked to the end of the mining supervision. The mine owner is initially responsible for securing abandoned mine workings and the mining authority imposes appropriate measures on him. If the actual owner cannot be identified, the safety measures are carried out at the expense of the state of North Rhine-Westphalia.
The mining authority has so far identified approx. 31 000 abandoned openings from mining (adit and shaft openings). The total of the areas that may be affected by residual mining cavities is currently approx. 600 km². In addition, the mining authority is aware of approx. 3700 collapses and sinkholes that have occurred in the country since the mid-60s of the 20th century.
In the course of the evaluation of mine maps held by the mining authorities - the graphic representations of the mine workings produced by mining companies the total number of abandoned mine openings and the sum of all areas that may be affected by residual mining voids will probably continue to increase. Unfortunately, a considerable number of mine maps and documents were lost during the world wars, meaning that the information on mining activities is incomplete.

In addition to the documented mining activities, further mining was carried out, however, the scope and extent of these extractions are either barely known or not known at all due to a lack of or insufficient documentation. These include, above all, the so-called 'Uraltbergbau' (mining before the creation of mine maps before the 17th century) or illegal mining carried out by the local population in times of lack of coal supplies (for instance after WWII).

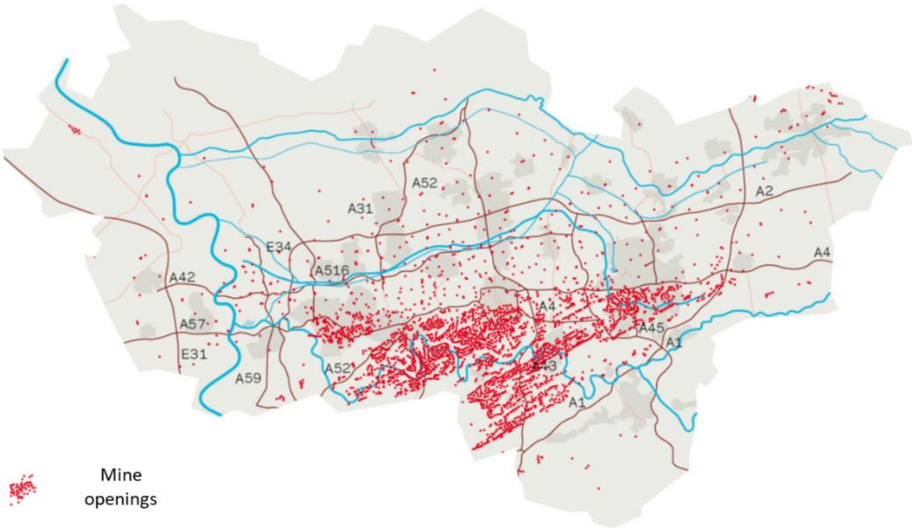


Figure 4 Former mine openings in North Rhine-Westphalia

The mining authority in NRW assumes the incidence of 90 sinkholes and collapses per year. In the Saar region, the 2nd importan hard coal mining region in Germany, 5 collapses occur per year.

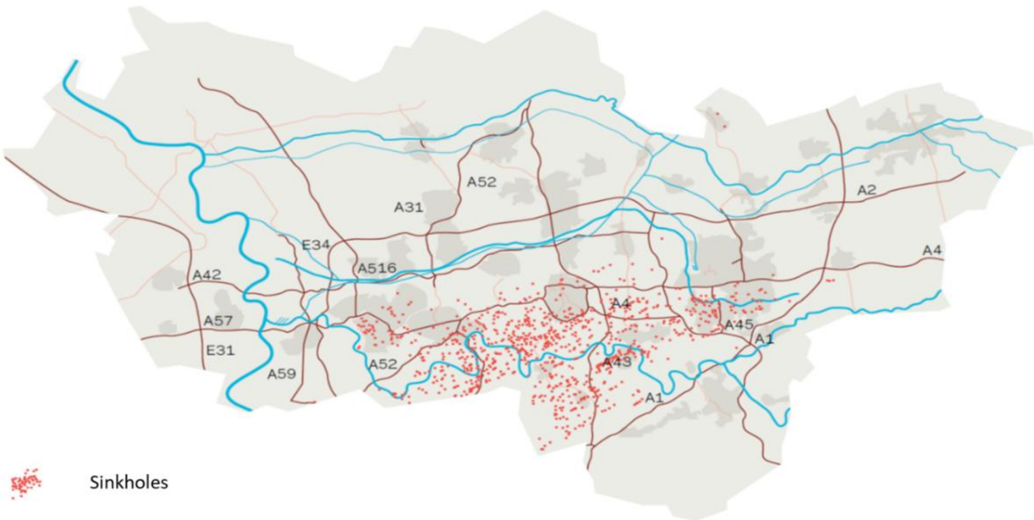


Figure 5 Sinkholes in North Rhine-Westphalia

Since 2011 the mining authority is recording surface collapses and damage to buildings as well as mine openings in a coordinated manner and is analysing their cause with the help of available documents and mine maps. The allocation of a damage location on the surface to mining excavations forms the basis for determining responsibility under regulatory and liability law and, accordingly, for allocating the obligation to pay costs.

Table 2 Sinkholes in North Rhine-Westphalia

Year	Sinkholes							Building damages			
	Cavities closed to surface				Mine openings			Statistically reported since 2006			
	mining induced	unknown	not mining induced	total	mining induced	not mining induced	total	mining induced	unknown	not mining induced	total
1986-2005	961	218	292	1471	184	23	207				
2006-2010	84	139	194	417	63	24	87	14	71	68	153
2011	21	32	52	105	29	2	31	2	19	21	42
2012	26	50	68	144	18	1	19	1	27	31	59
2013	17	41	50	108	19	0	19	0	26	24	50
2014	11	40	41	92	11	1	12	4	25	14	43
2015	18	41	57	116	19	0	19	1	23	27	51
2016	17	36	49	102	11	1	12	1	15	21	37
2017	8	32	52	92	8	4	12	1	22	25	48
2018	4	24	41	69	9	7	16	1	20	26	47
2019	9	23	45	77	13	2	15	0	26	25	51
2020	20	23	40	83	16	1	17	0	21	27	48
2021	27	37	53	117	16	5	21	3	14	11	28
2022	6	27	27	60	9	14	23	0	13	18	31
Sum 2006-2022	**268**	**545**	**769**	**1582**	**241**	**62**	**303**	**28**	**322**	**338**	**688**
Total since 1986	**1229**	**763**	**1061**	**3053**	**425**	**85**	**510**	**28**	**322**	**338**	**688**

Since 1986 more than 3000 cavities have been reported, almost 50% of them are induced by mining activities.

Sinkhole hazard in France

Like many other European countries, France has a long-held mining tradition. In French territory, the earliest evidence of underground mineral resource extraction dates back to the Neolithic age. The exploitation continued over the centuries. These were small artisanal exploitations. However, it was the industrial revolution (17^{th} - 18^{th} centuries) that constituted the decisive impetus in the rise of French mining activity. It was the birth of the major mining basins (coal, iron, salt, etc.).

Mining activity continued to flourish in France during the first half of 20^{th} century, mainly because of the two world wars. In the aftermath of the World War II, the national effort undertaken for the reconstruction of the country and the reduction of French energy dependence facilitated the revival of mining activity. The production of coal and lignite increased rapidly to 60 million tonnes in 1958, a record year. Different economic factors, the development of use of hydrocarbons in energy production, competition from other countries and the depletion of certain deposits have gradually generated the decline of French mining activity. Initiated in the early 1960s for coal and iron and in the early 1980s for the exploitation of other substances, this decline has accelerated since the early 1990s. Coal exploitation stopped in 2004.

The French post-mining is a wide story, there were more than 4000 “mining titles” in mainland France. Many substances were exploited: coal, iron, aluminium, uranium, salt, potash, gold, silver, and a lot of other metals. There are many coal mines throughout the territory, some of them are very old.

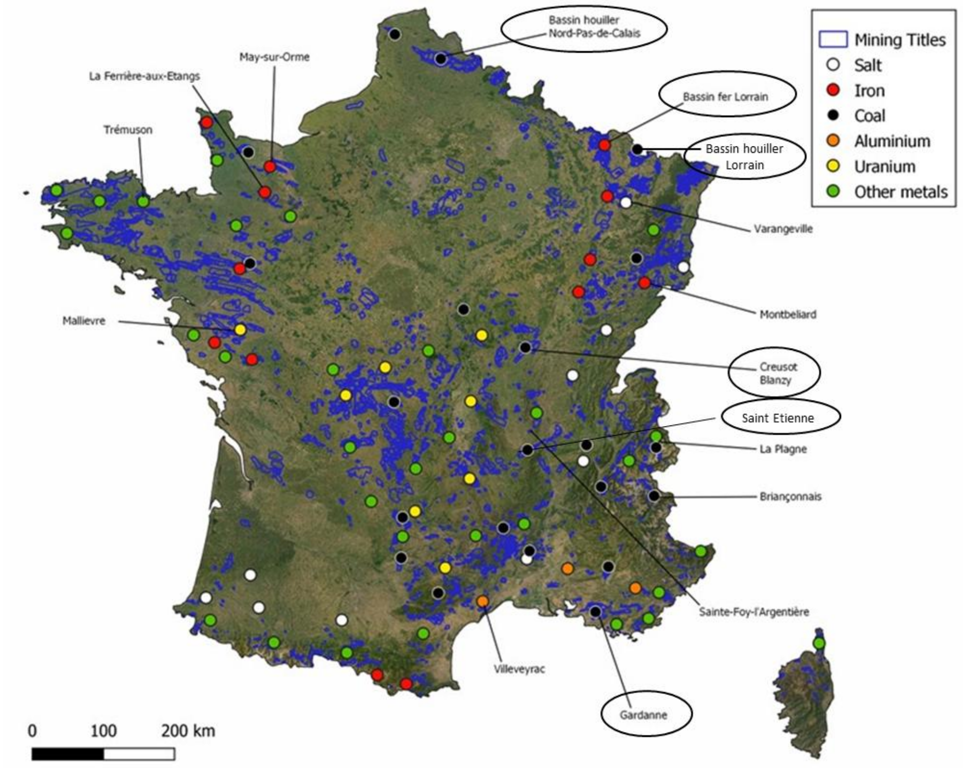


Figure 6 Mines in France (Points represent the main mines including the coal and lignite)

At the end of the 1990s, a series of major problems (subsidence, sinkholes) occurred in the Lorraine iron ore basin, affecting safety of persons and property in some cases. After these events, France developed a mining risk management policy and implemented various tools at first to make sure that the right expertise and research was in place, then followed that with operational tasks.

The first step is the law of March the 30th 1999. The main points are:

- Extension of the responsibility of the mining operator in the time and the space, taken back by the State at the end of the exploitation or the disappearance of the mining operator
- Implementation of the monitoring if the risk is not treated
- Land-reuse planification: Mining risk prevention plans (PPRM)
- Property exposed to a mining risk can be expropriated by the State

Currently, administrative and sovereign control is managed by the Ministry for the Ecological and Inclusive Transition and its Regional Division (DREAL). Mining expertise is carried out by an independent entity, GEODERIS, a French "Public Interest Group" between BRGM and INERIS. BRGM's Department of Prevention and Mine Safety is responsible for safety and operational management of facilities and safety equipment. INERIS and BRGM belong to the Scientific and technical network.

Figure 7 The French post mining organization

In France, all old mines are being studied. The aim is, for each phenomenon, to delimit areas where hazards exist and assess their level, in order to determine the risk for the existing stakes and the possibilities of construction or development in terms of land planning.

The first step is to collect and analyze old mining data: the configuration of mining works (depths, dimensions, exploitation methods, mining plans) and the characteristics of the environment: geology, hydrogeology. Some field investigations (light and non-heavy drilling campaigns) are carried out as well as a visit to the mine if it is accessible.

From the collected data, the phenomenon such as sinkholes are evaluated. The cross between the intensity of the phenomenon and its predisposition gives the level of hazard - it's a quantitative approach, then a map is made.

GEODERIS has carried out around 250 risk studies (large mining "sites" and those with many surface buildings). The results are 12 350 hectares of mapped hazards

In this context:

- Sinkhole phenomenon is studied in each hazards study.
- About 80% of the hazard areas are concerned by sinkholes.
- almost 4000 sinkholes identified (through archives or directly observed on former mining sites.
- Between 5 to 15 sinkholes appear each year.

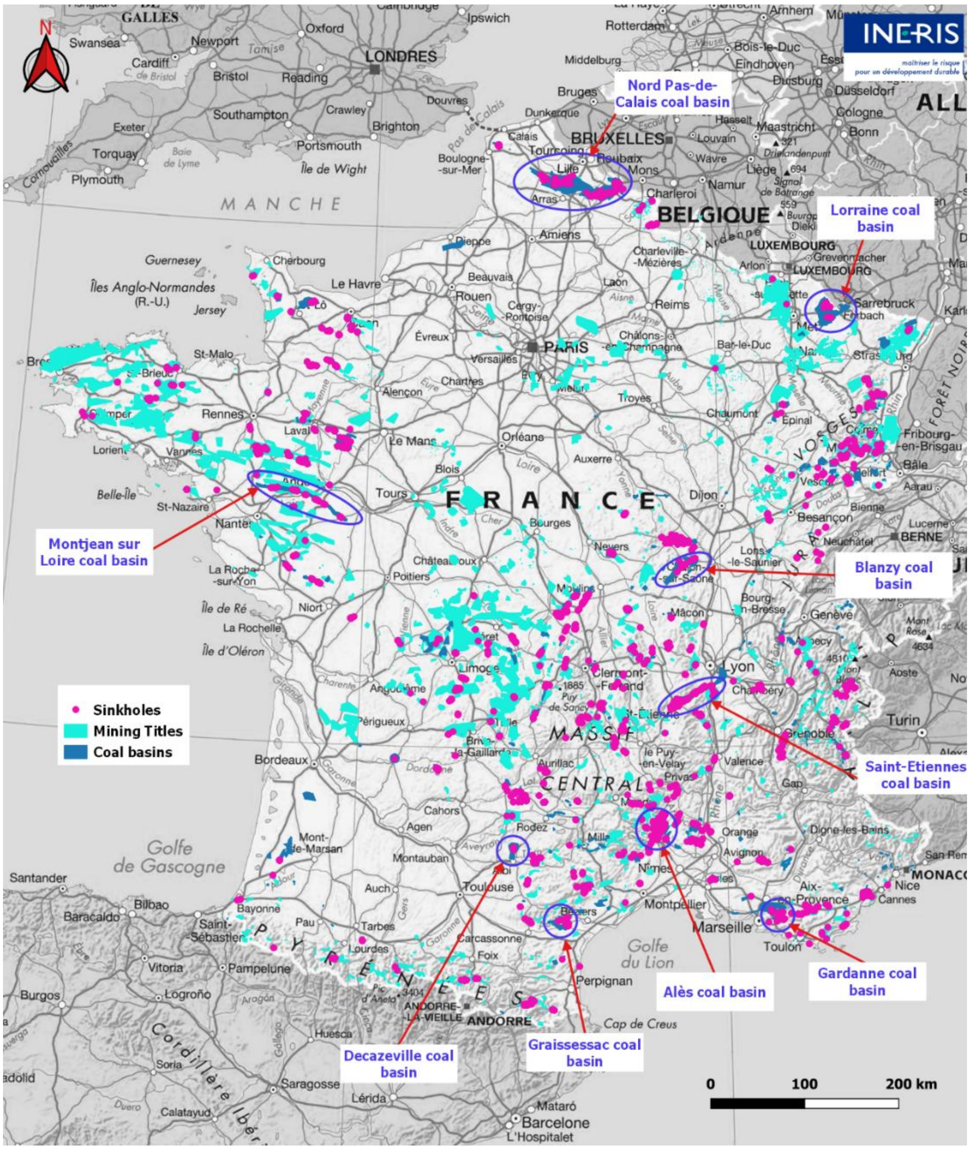


Figure 8 Map of the mining activities and sinkholes localization

Sinkhole or localized land collapses are characterized by the sudden appearance on the surface of a collapse crater, which generally varies from a few meters to several tens of meters in diameter. The depth of the crater depends mainly on the depth and dimensions of the mining cavities that caused it. There are several mechanisms that cause sinkholes: breakdown of the roof of a gallery / mining cavity, collapse of broken isolated pillar (s), collapse of a shaft head (backfilled or empty).

Figure 9 Some examples of sinkhole occurred in France (pictures from GEODERIS, France)

Post-mining sinkhole hazard assessment results from the cross-referencing between the intensity of the phenomenon and the predisposition. Intensity is the predictable diameter of the collapse. It depends on the width of the cavity and the thickness of the shallow non-cohesive soil layer. The second step is the assessment of predisposition. It's an expert analysis based on different criteria such as presence of similar phenomena on the site or in similar or identical configurations.

Studies have been carried out recently to improve the assessment methodology:

- 2016-2017: new grid for estimating the intensity of sinkholes.
- From 2024: reflection to define quantitative approaches to estimate the predisposition of old mining sites to sinkhole phenomena.

The objective of the current risk management policy in France is to preserve the safety of people. Risks can be treated by three different actions:

- eliminate the issues,
- remove the hazard by strengthening or filling the cavity,
- monitoring.

France has delegated operational management for risks related to old mines to BRGM (monitoring and treatment).

Given the large number of hazard areas identified in France, it seems difficult to eliminate all the challenges or all the hazards. For hazards that present no imminent danger for people, monitoring is preferred when:

- mining work is accessible from underground, it is monitored by visual inspection of the risk area.
- the areas to monitor are not accessible from underground or are dangerous, an instrumentation adapted to the risks is used.

Figure 10 Mining works inspection with camera and laser (left) or visual inspection (right) (pictures from GEODERIS)

When monitoring does not allow the risk to be controlled, other solutions to address the risk must be considered. In such cases, a technical-economic study of filling and, in parallel, an assessment of the cost of expropriation are carried out. The State then decides on the best solution basing on the assessments.

An example of expropriation is the case of the old coal mine of La Chapelle-sous-Dun. Old galleries are present under buildings between 5 and 20 m deep but there is no plan to locate them. Sinkholes have appeared in the area. Several drilling campaigns were carried out to find the galleries but not all of them were found. It was therefore impossible to fill all the mining voids. The authorities decided to expropriate the inhabitants: 9 buildings were destroyed in 2014, and the area was redeveloped into a green space.

Figure 11 The area impacted by sinkholes before and after expropriation (pictures from BRGM)

Sinkhole hazard in the Upper Silesia region of Poland

The identified threat of mining-origin sinkholes in Poland is limited to following five regions (1-5), where shallow mining of coal and ore minerals was or is still being carried out (Fig. 12):

1 - Upper Silesia and Lesser Poland,
2 - Lower Silesia,
3 - Lubusz and Poznań ,
4 - Świętokrzyskie
5 - Kuyavia and Pomerania.

The threat of sinkholes exists in areas of performed shallow mining as well as in areas of excavations that make the deposit accessible, such as shafts and transport, water and ventilation galleries. Only mining activities in areas 1 and 2 as well as sinkhole occurrences are relatively well documented cartographically. In these areas (coal and ore mining), sinkholes with diameters ranging from 1 to several meters were recorded in the past. They did not cause any significant damage to buildings due to small horizontal size of deformations. In several cases, they caused damage to road and railway infrastructure. This is due to the fact that most of these events occurred in forest or agricultural terrains. In 1977, a deep shaft collapsed at the area of operating coal mine Szczygłowice, causing significant damage to the mining infrastructure and the environment (Figure 13).

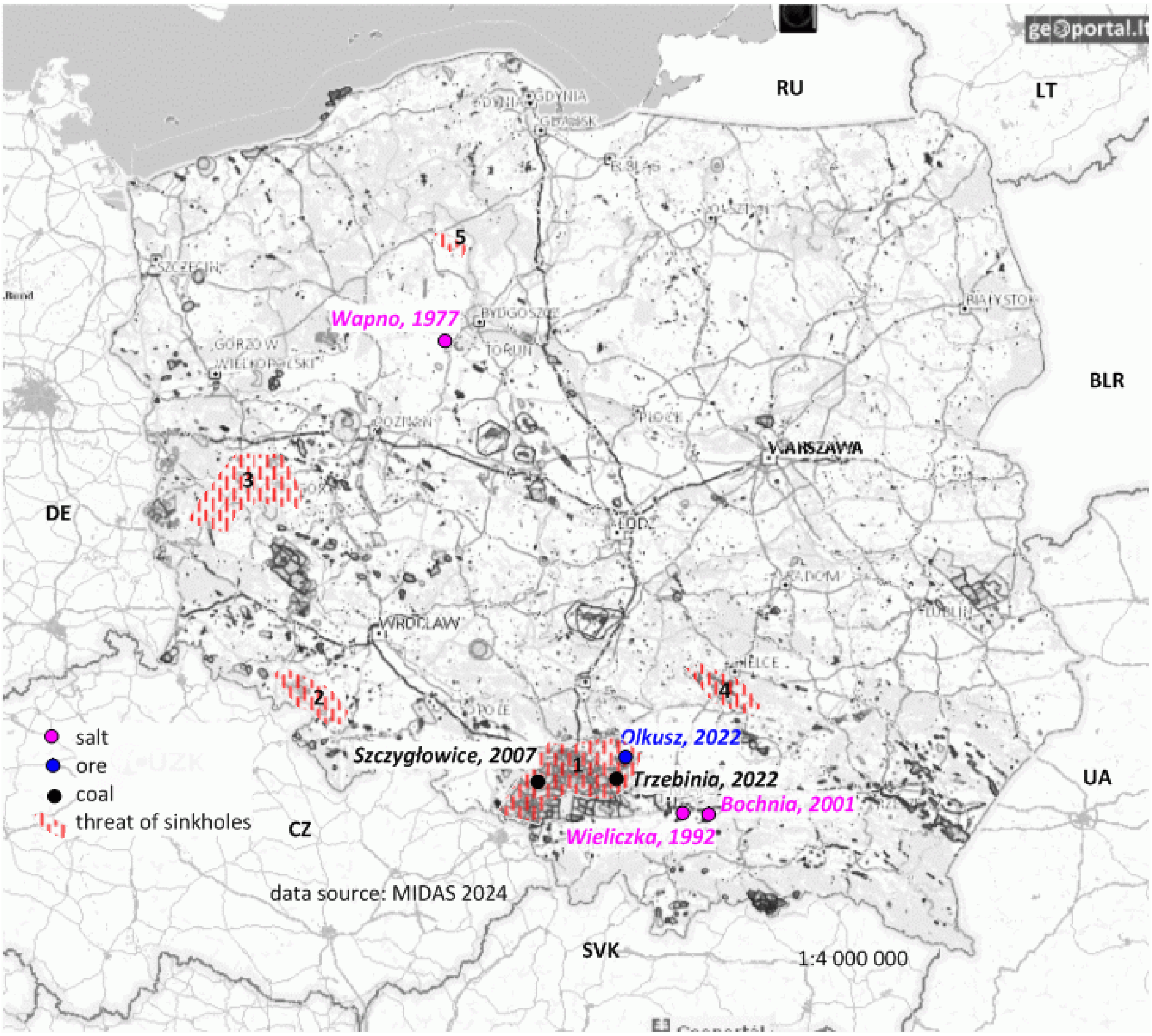


Figure 12 Regions in Poland with sinkholes threat on the background of mineral deposits and mining areas (source of mining and resources data: PIG-PIB, Geoportal/ MIDAS 2024).

The largest mine origin sinkholes in Poland (in terms of size) occurred in regions where rock salt was mined. Due to the significant size of these deformations, exceeding 100 m, they caused significant damage to buildings and infrastructure. All these events were caused by ingress of rain water into mine workouts and voids (Wapno 1977, Wieliczka 1992, Bochnia 2001).

a

b

Figure 13 A photo View of the sinkhole and damaged shaft structures at Szczygłowice mine.

In 1998, GIG (basing on data from the geological documentation of mines to depth 80m) developed a research project to assess the risk of mining sinkholes in the USCB and methods of its liquidation. As attachment to the project, an atlas of sinkhole hazard in the areas of shallow coal and zinc-lead metal ore exploitation in the Upper Silesian Coal Basin (USCB) was created. It was done on sections of cartographic maps at scale of 1:25 000. The identified number of sinkholes collected in period 1967-1998 by mines' operators was 452. The project proposed a method and criteria for quantifying the hazard and required actions needed for the development of such areas for engineering purposes. In 2005, GIG began digitizing mining maps from the USCB region. In 2015, a web application called sinkholes (zapadliska) was launched at address www.zapadliska.gig.eu. It provides data on the location of abandoned mines, regions of shallow exploitation up to depth 100 m, shafts location and sinkholes that have been recorded. Since then, data on sinkholes have been updated continuously and are presented in web service on-line (Figure 14).

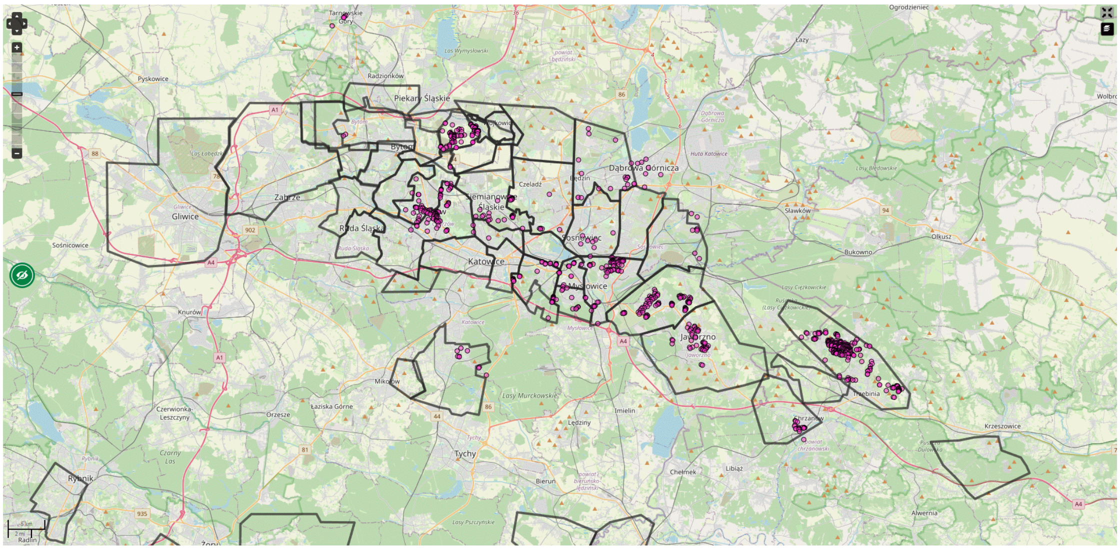


Figure 14 Abandoned hard coal mines in the Upper Silesia and Lesser Poland and sinkholes recorded in years 1967-2024 (www.zapadliska.gig.eu)

The intensity of the sinkhole threat increased in years 2022-2024 on terrains of two closed mines, located in Upper Silesia and Lesser Poland, being in the last stage of flooding process (flooding water front in depth interval 0-20m). One of these mines was extracting lead and zinc ore in Olkusz area (Pomorzany mine). The second mine exploited hard coal in Trzebinia area (Siersza mine). The photo views of selected sinkholes from these mines are presented in Figure 15.

a b

Figure 15 Selected sinkholes recorded in mines Siersza (a) and Pomorzany (b)

In a short period of time, several sinkholes occurred in the above-mentioned mines. These events caused great media interest and concern among the communities living in the communes of Trzebinia and Olkusz.

<u>Sinkhole hazard in Spain</u>

The main and most important coal basins are concentrated especially in the north of Spain, although the importance of the other basins and the relevance of their mining activity in the industry and economy should also be mentioned.

There are currently no active coal mines in the country. La Escondida mine, in León, was the last underground coal mine to be closed and decommissioned in December 2018.

In Spain, several coal mining basins have experienced subsidence problems over the years due to intense mining activity. Subsidence is a geological phenomenon that occurs when the ground sinks due to the extraction of minerals, as in the case of coal, leaving underground voids that can cause the overlying material to fracture in a slow and progressive process.

Spain elaborates a map delimiting the areas with different types of movements such as those related to mining operations, representing the most intense and frequent movements. This map, published in 1987, was developed by Mercedes Ferrer Guijón from the Geological and Mining Institute of Spain in response to the need for information on geological hazards and risks on a national scale.

The original map shows current and/or potential landslides and subsidence linked to open-cast mining, current and/or potential subsidence linked to dissolution mining and the movements that are of interest to us: current and potential subsidence linked to underground mining and current and/or potential subsidence linked to open- pit and underground mining. We have analysed the last two types of movements and the relationship with the locations of the coal mining basins in Spain and have obtained the following figure.

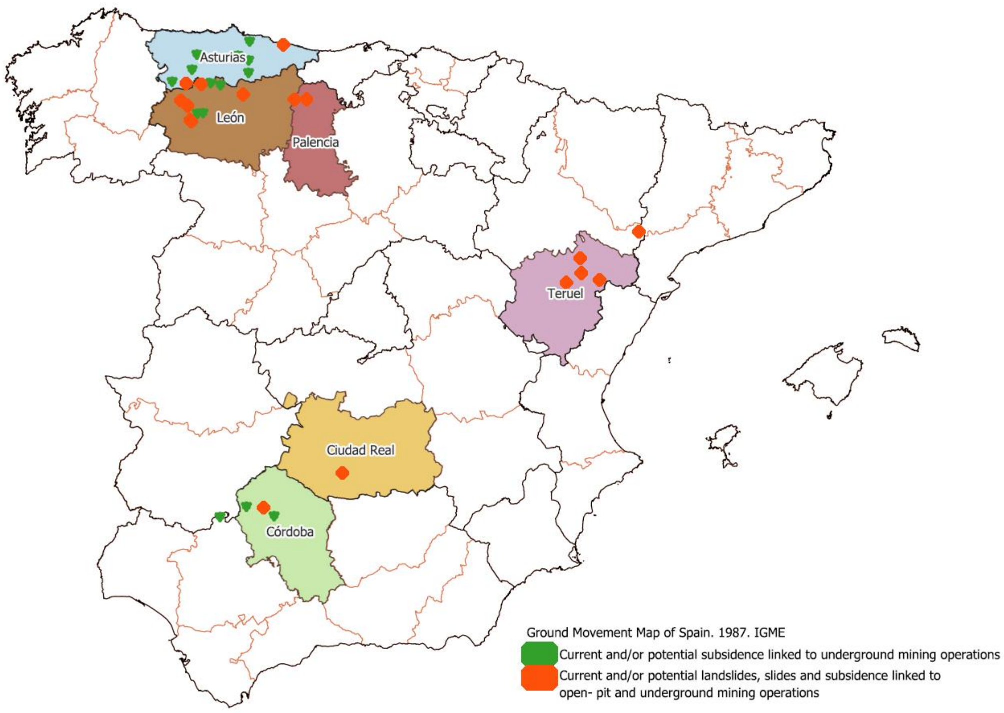


Figure 16 Main coal basin municipalities and ground movements related to underground mines

The main clusters of underground workings belong to the León-Palencia-Asturias area with coal workings, the Teruel area with lignite workings and the northern area of Córdoba, Spain.

The areas with the highest risk of subsidence in Spain due to mining activity and the main coal basins to which they belong are described below.

The Asturian Central Basin is the largest coal basin in Spain and includes the towns of Mieres, Langreo, San Martín del Rey Aurelio. In Asturias, coal mines have reached considerable depths, with some of the deepest mines reaching 700-900 meters below the surface. Mines such as 'María Luisa Shaft ' in Langreo and 'Fondón Shaft ' in Mieres.

In the Caudal Basin, the main municipalities are Lena, Aller, Mieres and Riosa. The Nalón Basin, where significant depths were also reached, generally in the range of 600-800 metres.

In the province of León, the Carboniferous Basin includes the areas of Laciana, Fabero, Torero and La Robla. In the areas of Laciana and El Bierzo, subsidence has been a relevant problem, the coal mines have had depths varying between 300 and 700 meters. In the region of Laciana, for example, underground mining reached considerable depths, although generally less than in Asturias.

The Palencia Basin is in the north of the province of Palencia, in Castilla y León. It extends through municipalities such as Guardo and Barruelo de Santullán. The mines have reached depths of up to 600 meters. Coal mining in this area was intense during the 20th century, with some very deep mines.

The Teruel Mining Basin, this basin is known for the mining of lignite. The Andorra-Sierra de Arcos area is the most representative. Lignite mines in the province of Teruel are shallower compared to the hard coal and anthracite mines in the north of Spain. These mines are usually found at depths of between 100 and 400 meters.

In the province of Cordoba, this basin focused on lignite mining, also known as the Guadiato basin, where coal beds are mined in Peñarroya-Belmez-Espiel. Lignite mines in the Guadiato basin also tend to be shallower, generally in the range of 100 to 300 meters.

In general, coal mines in Spain have ranged from shallow open-pit mines to underground mines reaching depths of almost a kilometer in some basins in the north of the country. The greatest depths are recorded in Asturias. Most of the coal mines in the basins named above have been mined by the longwall method because of the way the coal layers have been formed.

Due to the depth at which the coal mines in our country have been exploited, there are no records of large undercuts. There are records of pits produced by coal mining operations, located in the Asturian area, but the data are not publicly available.

The mining companies, which have historically been responsible for operating and managing the mines, are often the only entities that have detailed information on the mines. These records often include technical data such as maps of underground galleries, geological surveys, incident reports and associated risk analyses. However, due to the private nature of these companies and the sensitivity of the information, the data is often not shared outside the corporate or management environment.

5. Methodology

The methodology of the SIRIMA project is based on the following main steps:

- The creation and the analysis of a large-scale database and using advanced data analysis tool such as: multi-regression analysis, multi-criteria analysis;
- The development of a website for different end-users;
- The application of an advanced numerical modelling to better understand the mechanism of the sinkhole and the damages induced on structures and infrastructures;
- The development of an operational reliability tool to better mitigate, reinforce, existing structures and infrastructures in the post-mining area where potential sinkhole can occur.
- The development of the operation monitoring tool using the different existing techniques.
- The development of a machine learning method, a technique that can allow to find new elements that may remain imperceptible when using previously used research and modelling techniques.

Each step of the methodology will be discussed and analysed basing on the case studies and the in-situ observations. Where there is insufficient information to apply machine learning techniques, approximate data will be used.

5.1. Project implementation path

The project was divided into six work packages entitled:

- WP1. Project management and coordination.
- WP2. Data bases creation and advanced analysis.
- WP3. Mine flooding impact on surface instability.
- WP4. Sinkhole hazards and risks related to shallow mine workings.
- WP5. Machine learning modelling.
- WP6. Valorisation, dissemination and exploitation of the results.

The following problems will be addressed in the project:

- WP2: Preparation of a database of post-mining areas. The database will contain information on areas of shallow mining exploitation of coal and metal ore deposits and registered sinkholes within the project partner countries; data on induced or natural seismicity (if any), changes in the level of the groundwater table (actual measurement), surface deformation (subsidence and uplift, occurrence of discontinuities – InSAR technology), changes in the distribution of the gravity field of the rock mass (deformation of the rock mass), metadata on geology, tectonics and knowledge on processes and consequences related to the flooding of the mine.
- WP3: Estimation of the relationship between mine flooding and the possibility of activation of sinkhole processes. Development of criteria for assessing the risk of mine flooding in a selected area (Siersza test site). Development of proposals for the classification of post-mining areas with regard to hazards related to the restoration of the natural level of underground water (mainly sinkholes).
- WP4: Estimation of risks and threats related to the occurrence of sinkholes in post-mining areas. Application of various computational, simulation and modelling methods in attempts to predict the risk of sinkholes in post-mining areas and assessment of the impact of sinkhole or subsidence trough development on the ground surface and existing land development (buildings or technical infrastructure).
- WP5: Artificial Intelligence (AI) techniques. Modelling using Machine Learning (ML) and Deep Learning (DL) methods. Creation using a model that allows estimating the risk of sinkholes in a post-mining area.
- WP6: Dissemination of project results. Development of a Decision Support System for post-mining areas at hazard of subsidence processes.

A detailed description of each WP is provided in sections 4.2.1 – 4.2.6 of this document.
Based on the presented Work Package issues, a project implementation path and mutual connections between individual WPs were developed:

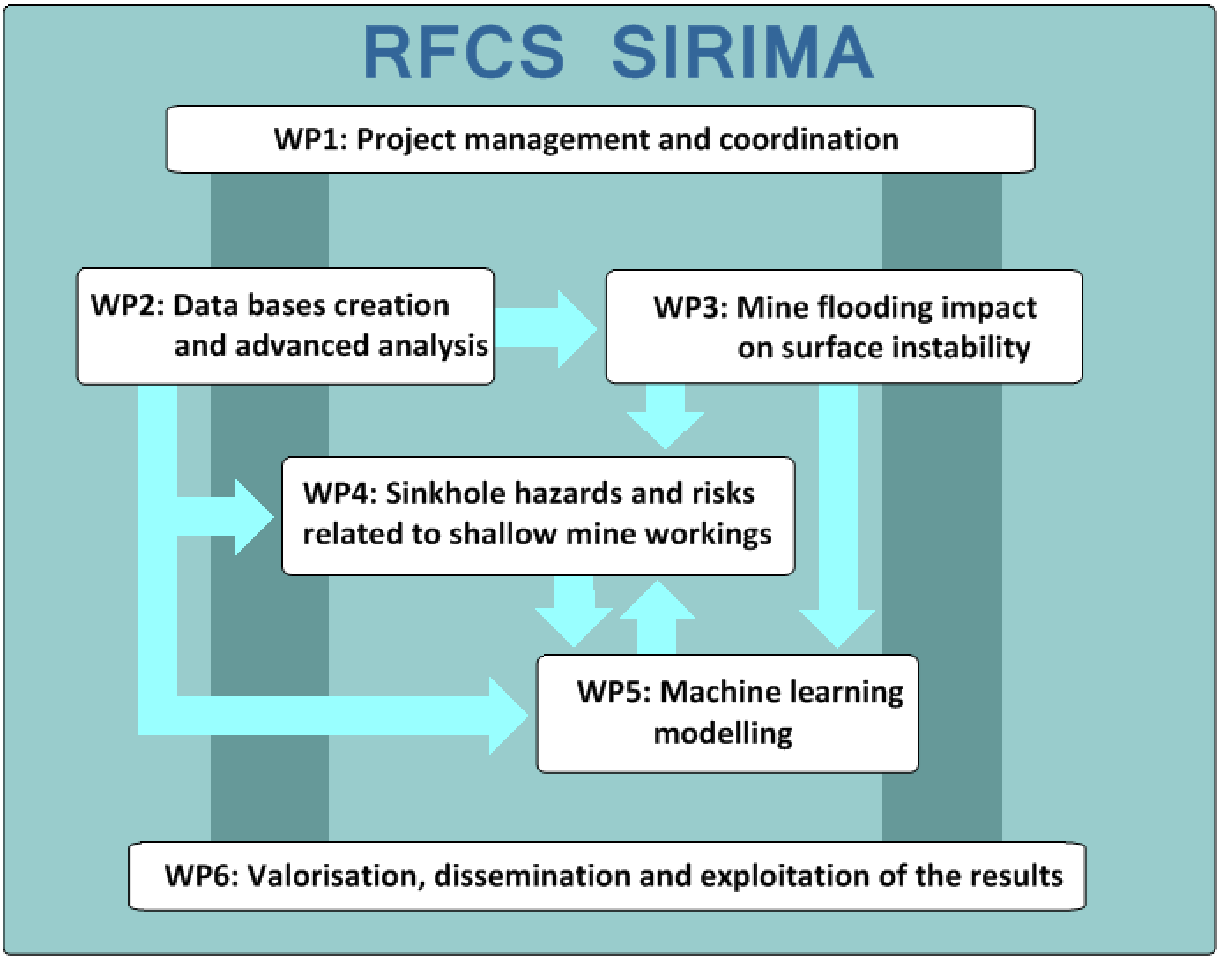


Figure 17 Graphical presentation of the SIRIMA project workflow.

5.2. Project implementation

As part of the project, 6 Work Packages are planned, which organize the work on subsequent aspects of the hazard of formation of the sinkholes.

5.2.1. WP1. Project management and coordination.

WP Leader: GIG-PIB, Participants: all Partners

The objective of this work package is to manage the project elements, to assure the smooth progress of the project and the rational use of resources. The Work Package is conducted throughout the duration of the whole project and involves the participation of all members of the Project Consortium.

Specific objectives of WP1 are:

- To formalize the joint research structures and prepare the Consortium Agreement;
- To assure that the project progresses as scheduled;
- To guarantee that effective communication and collaboration is maintained between partners;
- To prepare and submit the reports (Technical and Financial), by the deadlines set by the Commission;
- Project execution on budget and on schedule;
- Dissemination of results through workshops, website, papers and articles (SIRIMA DECP);

The Work Package has been divided into three tasks, a detailed description of each task is presented below.

Task 1.1. Project coordination

Task Leader: GIG-PIB; Participants: -

Goals:

- preparation and implementation of the Consortium Agreement,
- monitoring the fulfilment of project obligations by all Partners,
- guarantee effective communication between partners and the European Commission,
- informing the EC about any changes in the project,
- submission of all documents to the EC,
- organizing the project meetings.

GIG-PIB as the coordinator, will be responsible for technical supervision and administration of the project.

This task comprises the activities of GIG-PIB regarding the general organisation and legal aspects of the project, including the preparation of a Consortium Agreement, the organisation, chairing and attendance at project-meetings. It will also include the activities required to reporting requirements, including the synthesis and presentation of reports and financial reporting.

The co-ordinator will ensure that suitable technical and financial reports are submitted on time to the Commission. The coordinator's activities will cover reporting requirements, including the synthesis and presentation of reports and financial reporting according to the deadlines set by the European Commission. Within this task the comprehensive overview, Mid-term Report as well as the Final Report will be elaborated in accordance with the parameters set by the Commission. The reporting process will be supervised and coordinated by GIG-PIB. GIG-PIB will also be responsible for presentation of the reports at the TG meeting. Reports will be based on information concerning progress of all activities delivered by the project partners. WP leaders will be responsible for technical co-ordination of their particular packages and preparation of draft technical progress reports for their WPs.

Related documents:
Deliverable D1.1 – Comprehensive overview of the SIRIMA Project. 31.12.2024
Mid-Term Project Report (up to 60 days after 18 months of project implementation) 01.03.2026
Final Project Report (up to 60 days after 36 months of project implementation) 29.08.2027

Task 1.2. Website management

Task Leader: GIG-PIB; Participants: INERIS, BRGM, DMT-THGA, IMG-PAN, SUBTERRA, UL, GEODERIS

Goals:
- creation of the project website,
- updating of content and data presented in the individual tabs of the website,
- entering data into a separate common space for the purposes of analyses and modelling conducted by the project partners,
- mutual sharing of data and work results by the partners.

GIG-PIB will create and manage the project website. It will serve to inform and coordinate the project. This task will comprise the activities to be carried out in order to set-up and maintain the project website, which will be used for both collaborative information sharing in a private area and to inform the wider public about project. All of the partners will provide information on the project.

Related documents:
Milestone 1 – project website. 31.12.2024

Task 1.3. Project management and coordination

Task Leader: GIG-PIB; Participants: INERIS, BRGM, DMT-THGA, IMG-PAN, SUBTERRA, UL, GEODERIS

Goals:

- implementation of the project in accordance with the budget and schedule,
- supervision of the project progress,
- ensuring timely submission of the reports (Technical and Financial) to the European Commission,

This task comprises the activities to be carried out by the project coordinator - GIG-PIB and all partners to ensure that the work progresses as scheduled, as well as the correct use of resources. With regard to the administrative, financial and technical aspects, controls will be implemented in a manner that assures a smooth operational sequence of the project. The financial reports will be compiled by GIG-PIB from the individual financial reports prepared by the partners.

Related documents:
Deliverable D1.2 – Dissemination, Exploitation and Communication Plan of SIRIMA Project. 31.12.2024
Deliverable D1.3 – Public publishable report 30.06.2027

5.2.2. WP2. Data bases creation and advanced analysis

WP Leader: INERIS, Participants: GIG-PIB, BRGM, DMT-THGA, IMG-PAN, SUBTERRA, GEODERIS

The main goals of this WP are:

- collection of data and metadata,
- development of reference databases,
- identification of post-mining areas with sinkhole hazard due to shallow mining works
- data analysis of mine flooding processes
- monitoring of field sites

WP2 is the starting point for the implementation of subsequent WPs. Within this WP, all Partners will organize basic databases supplementing them with information on the countries they come from. The collected data and metadata will concern, among others, shallow mining exploitation of hard coal deposits and/or metal ores in the areas of liquidated mines, for which the partners will obtain data from their own resources, archives of their countries or publicly available sources. Data will be collected on sinkholes that have been observed and recorded so far. These will be two basic databases for further analyses and modelling. Additionally, an analysis of the process of flooding selected mining areas of liquidated mines will be carried out, in order to assess the techniques and methods of estimating this process. This information will be used to assess the relationship between mine flooding and the potential intensification of sinkhole processes. The WP2 also includes conducting in-situ research and measurements within the already prepared test sites (Thil, Kazimierz-Juliusz) as well as establishing and conducting monitoring on a new test site (Siersza), based on the experience gathered at the previous two testing grounds.

The Work Package has been divided into four tasks, a detailed description of each task is presented below.

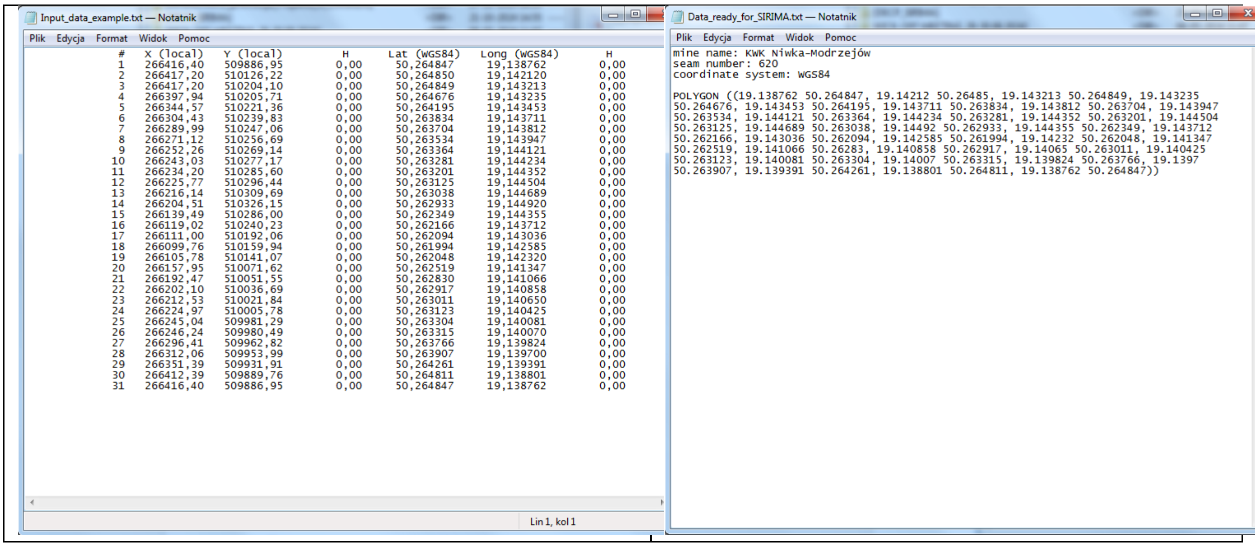
Task 2.1. Data base of shallow coal mining exploitation in abandoned mines in the partner's countries.

Task Leader: GIG-PIB; Participants: INERIS, BRGM, DMT-THGA, SUBTERRA, GEODERIS

Goals:

- collection of data and metadata,
- identification of post-mining areas with sinkhole hazard due to shallow mining works,
- presentation of results in the form of an interactive map provided via the website.

All Partners will prepare and provide the GIG-PIB team responsible for this task with data on shallow mining of hard coal and/or metal ore deposits in the areas of abandoned mines in their countries, which they will be able to obtain basing on their own resources, archives in their country or publicly available collections. The prepared data will primarily include data files containing fields of exploitation with a description. Each field of exploitation should include one number, geodetic coordinates in the local geodetic system, coordinates converted to the universal WGS84 geographic coordinate system, as well as information on the name of the mine, the name of the deposit (coal or ore), its refinement (designation of the coal seam or other). This data will be processed and adapted for presentation on a publicly available, free map base (e.g. OpenStreetMap).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seam number: 620
coordinate system: WGS84

POLYGON ((19.138762 50.264847, 19.14212 50.26485, 19.143213 50.264849, 19.143235
50.264676, 19.143453 50.264195, 19.143711 50.263834, 19.143812 50.263704, 19.143947
50.263534, 19.144121 50.263364, 19.144234 50.263281, 19.144352 50.263201, 19.144504
50.263125, 19.144689 50.263038, 19.14492 50.262933, 19.144355 50.262349, 19.143712
50.262166, 19.143036 50.262094, 19.142585 50.261994, 19.14232 50.262048, 19.141347
50.262519, 19.141066 50.26283, 19.140858 50.262917, 19.14065 50.263011, 19.140425
50.263123, 19.140081 50.263304, 19.14007 50.263315, 19.139824 50.263766, 19.1397
50.263907, 19.139391 50.264261, 19.138801 50.264811, 19.138762 50.264847))
```

Figure 18 Example of an area of shallow mining exploitation for the purposes of task 2.1.

Basing on these data, the website presenting the areas of shallow mining and the resulting sinkholes at the European Union level will be created but the scope of information will be limited to the countries from which the project partners come from.

Related documents:
Deliverable D2.1. Shallow coal mining in Europe 31.08.2025

Task 2.2. Data base development of sinkholes due to shallow mining works

Task Leader: INERIS; Participants: GIG-PIB, BRGM, DMT-THGA, IMG-PAN, SUBTERRA, GEODERIS

Goals:

- collection of data and metadata,
- development of reference database,
- sinkhole database.

The partner responsible for the implementation of the task – INERIS – will prepare a proposal for a database on sinkholes and present it to the partners. This proposal will be verified by the partners until a common position is developed. Then, the partners will collect the maximum number of well-documented cases of sinkholes from their countries. These cases will contain data on the conditions in which these events occurred, including information on their characteristics (dimensions, depth, damage to the surface, origin of collapse etc.) and about the mining conditions (depth, period of conducting, type of mining works, working thickness, shaft deep). The overburden characteristics will also be described (geology, roof fracturation, material overburden resistance, etc.). The analysis of all this information using a statistical tool will be carried out in other Work Packages. Basing on the data obtained, a public, simplified geodatabase will be created, which will be included on the map created in task 2.1.

Related documents:

Milestone 2 – Structure of the data base	31.12.2024
Deliverable D2.2. Sinkhole database	31.12.2025

<u>Task 2.3. Data analysis of mine flooding processes</u>

Task Leader: GIG-PIB; Participants: INERIS, BRGM, DMT-THGA, IMG-PAN, SUBTERRA, GEODERIS

Goals:

- collection of data and metadata,
- data analysis of mine flooding processes in selected test sites and in the coal basin scale,
- climate and weather conditions.

In this task, for the selected research site (Siersza mine in USCB – Poland; Thil mine in the Lorraine iron basin – France), a characterization of the mine flooding process will be carried out, basing on the analysis and assessment of archive and current results of monitoring of the groundwater table level. Additionally, analysis of the mine flooding process will be carried out against the background of geological, hydrogeological and mining conditions of the analysed area and, depending on the scope and availability of data, also taking into account information, e.g. on the physical-mechanical parameters of rocks saturated with water during the flooding of mining excavations. There will be analysed a long-term climatic conditions in the area of the analysed research sites (intensity, time period, amount of atmospheric precipitation) and an attempt will be made to assess the impact of changes in weather conditions on the course of the mine flooding process (in its final period) and to assess this factor as one of the elements shaping the possibility of occurrence of geodynamic phenomena on the surface. Data concerning the factors determining the course of the mine flooding will be compiled in a database, which will enable effective exchange of knowledge and experience in this area between project participants.

An important element of the task is the exchange of knowledge between partners on areas of closed underground coal mining and on the processes and effects related to mine flooding, as well as the experiences of countries in which these processes occurred in the past.

Task 2.4. Monitoring of endangered areas

Task Leader: DMT-THGA; Participants: GIG-PIB, INERIS, BRGM, SUBTERRA

Goals:

- collection of data,
- construction of a monitoring system,
- monitoring of field sites.

The task is planned to maintain the environmental monitoring systems developed so far for the test sites and to build such a system from scratch for the Siersza test site, where sinkhole processes have significantly intensified in recent years. The project includes 3 test sites:

1. Kazimierz Juliusz (Poland)
2. Siersza (Poland)
3. Thil (France).

In each of these test sites, processes posing threats to the surface resulting from mining operations conducted in the past are observed. At test site 1 - Kazimierz Juliusz, it is planned to supplement the monitoring system with the Postminquake project and the integration of the *e.cenaris* web-monitoring platform to share data in real time. In test site 2 - Siersza, it is planned to create completely new monitoring elements where the greatest intensity of the formation of new sinkholes is observed. Ineris will participate in the designing of this monitoring system. In France (test site no 3), existing and newly acquired data from the in-situ system in place will be made available to the project free of charge. The location of new measurement points will be determined strictly in accordance with the analyses carried out in WP2.

5.2.3. WP3. Mine flooding impact on surface stability

WP Leader: GIG-PIB, Participants: BRGM, DMT-THGA, IMG-PAN, SUBTERRA.

Main goals of WP3:

- development of a methodological guide for conducting the mine closure process by flooding,
- development of risk assessment criteria when flooding a coal mine,
- Identification of geological and hydrogeological factors causing the formation of sinkholes,
- time correlation of the rising groundwater table with the formation of sinkholes,
- proposal of classification system for post-mining areas based on their vulnerability to various risks related to the flooding of coal mine, including sinkholes, surface flooding, and floodplains.

Basing on the data archived and collected in monitoring (WP2), study of mine flooding processes will be carried out as part of WP3. After a deep analysis of hydrogeological processes related to the process of flooding the mine and restoring the natural aquifer, the relationship between the location of the water table and the activation of sinkholes and uplift processes will be sought. These data will be compared with the results of research on this phenomenon conducted, among others, in WP2 and with the results of computer simulations carried out in WP5. A common set of criteria for the assessment of post-mining areas of flooded mines will be proposed. As part of the WP3, it is planned to create a classification of post-mining areas of flooded mines due to the possibility of exposure to a risk or intensification of unfavourable phenomena (sinkholes, flooding and floodplains) as phenomena threatening public safety. Simultaneously, an attempt will be made to analyse the impact of natural and technical factors on the risk of occurrence or intensification of sinkhole phenomena.

This Work Package has been divided into three tasks, a detailed description of each task is presented below.

Task 3.1. Verification and optimization of the process of flooding of mine workings over the time.

Task Leader: GIG-PIB; Participants: DMT-THGA

Goals:

- development of risk assessment criteria when flooding a coal mine ,

- development of a methodological guide for conducting the mine closure process by flooding.

The management of sinkhole risk in post-mining areas is associated with several major uncertainty factors. While the geological structure in post-mining areas is generally well known, as is the spatial location of mining excavations, the main uncertainty is caused by the correct identification of the degree of rock mass disturbance after the end of mining activity. The behaviour of the rock mass subjected to diverse discontinuous deformations in the presence of post-mining voids under the influence of water is the main uncertainty factor in relation to the assessment of the possibility of sinkhole hazard.

The influence of the process of flooding and re-saturation of rock masses on their stability in the presence of mining voids is indisputable. The rate of change of rock properties in the presence of water (reduction of their strength and increase of deformability) is also significant, which directly depends on the rate of flooding of mining excavations, which strictly depends on the water absorption of the rock mass (Bukowski 2000, 2002). The average rate of water rise in flooded mine workings varies from 1-2 to a dozen cm per day, less frequently $t > 0.5$ m/d (Bukowski 2024). Water table may be overtaken by the rise of capillary zone by several dozen cm to even 2 m, or more, due to the saturation of the mine atmosphere above the water table with water vapor. In this zone, very rapid and intensive changes in the strength properties of the rocks occur. There is a rapid decrease in the compressive strength of the rock mass around the post-mining void filled with water, especially at the boundary of the liquid and gas phases in the pores of rocks previously drained of free water.

Considering the fact that in sandstone rock mass such as that occurring in the Siersza Coal Mine, the process of capillary saturation of the rock sample takes place in a short time - a few cm in 1-2 hours (Bukowski 2024), i.e. faster than the rise of the water table, the effect of mine flooding on the reduction of the strength of the rock mass and the increase in the risk of collapse is the greater the weaker and more water-absorbing rocks in the vicinity of the mining workings.

The effects of underestimating or overestimating the time of mine flooding have been discussed in Poland many times in publications from the first decade after 2000. On this basis and basing on the experience from the Siersza area, it can be stated that determining the rate of mine flooding and controlling this process and verifying the forecasted time of flooding are of key importance for determining the depth and time criterion for taking preventive measures. Due to the very large discrepancies between forecast calculations of the time of mine flooding, it is important to select the correct forecasting method and forecast parameters for hydrogeological conditions and geological structure as well as rock mass properties, which is one of the tasks of the SIRIMA project. The impact of mine flooding

on the increase in the risk of sinkholes is indisputable, but its intensity and connection with the frequency of sinkhole phenomena has not yet been sufficiently documented.
The implementation of this task is divided into several parts, which include:

- a review of methods for forecasting the course of the mine flooding process - based on literature data and on the consortium members' own experience, the methods for forecasting the process of flooding mine workings and drained rock mass will be analysed, including methods based on deterministic treatment of natural and technical factors (e.g. analytical and modelling methods) and statistical methods,
- characteristics of the strengths and weaknesses of each of these methods and indication of the possibilities and conditions of their application,
- comparison of the actual course of the mine flooding process constituting the research testing ground (Siersza mine - Poland) with forecasts of the course of this process made in 1999 (at the final stage of mine operation) and in 2006 and 2013 (verification of forecasts based on the monitoring data),
- indication of the reasons for the discrepancies between the mine flooding forecasts and the actual course of this process,
- indication of the ranking and characteristics of the main natural and technical factors determining the time and course of mine flooding and assessing their mutual dependence (based on, among others, forecasts of the mine flooding process and the results of the actual course of this process),
- developing a guide for planning and forecasting the mine flooding process, taking into account the strategy for reducing the risk of deformation on the ground surface.

Task 3.2. Correlation analysis of the occurrence of sinkhole phenomena with the level of the groundwater table

Task Leader: GIG-PIB; Participants: DMT-THGA

Goals:

- identification of geological and hydrogeological factors causing the formation of sinkholes,
- time correlation of the rising groundwater table with the formation of sinkholes.

Building on data collected in previous tasks, particularly T1.3 and T2.1, this task delves deeper into understanding the intricate relationship between sinkhole occurrences and fluctuations in the groundwater table. The data collection process will involve the systematic gathering of spatial and temporal information related to sinkholes and land uplift processes. These data will be subjected to rigorous analysis to uncover correlations and causal relationships.

The primary objectives of this task include identifying the key geological and hydrogeological factors that trigger sinkhole formation and quantifying their influence. By comparing our findings with research results from WP1 and the outcomes of computer simulations conducted in WP4, we will contribute to a more comprehensive understanding of this phenomenon.

The spatio-temporal analysis undertaken here will result in informative visualizations and descriptive reports that highlight the coincidence of excavation flooding in abandoned mines with the timing and geometry of sinkhole occurrences. This task's findings will be crucial in developing early warning systems and risk assessment strategies for sinkhole-prone regions.

Scope of work planned within the task:

- indication of the main natural and technical factors determining the occurrence of discontinuous deformations in the areas of active and liquidated mines, together with their characteristics and hierarchy,
- development of a method for determining the zones of sinkhole hazard for the surface due to changes in hydrogeological conditions in connection with the flooding of mines,
- development of criteria for selecting the type and parameters of protection in the conditions of flooding and dewatering of liquidated mines in the aspect of protecting the surface from the sinkhole risk,
- temporal and spatial correlation of the occurrence of sinkhole phenomena in the conditions of mine flooding (fluctuations of the water table, depth of the underground water table, etc.), against the background of the geological structure and technical and mining conditions (e.g. former underground mining infrastructure, method of its liquidation, etc.).

Related documents:
Deliverable D3.1 – Technical Report on Flood Risk Assessment and Mitigation Strategies for Liquidated-Abandoned Mines. 28.02.2027

Task 3.3. Predictive numerical models and classifications for assessing complex surface response in the area of flooded abandoned mines.

Task Leader: SUBTERRA; Participants: GIG-PIB, BRGM, IMG-PAN

Goals:

- review of existing methods and algorithms,
- predictive numerical simulations,

- proposal of classification system for post-mining areas based on their vulnerability to various risks related to the flooding of coal mine, including sinkholes, surface flooding, and floodplains.

For the development of the task 3.3 it is intended to propose a unified criterion for the assessment of flooded and abandoned mining areas. The construction of this criterion will be carried out through several actions:

- A classification will be made of mines that are flooded and may be exposed to risks such as sinkholes, floods or floodplains and at the same time threaten public safety. Database crated in Work Package 2 will be starting point of this classification.
- The impact of natural and technical factors on the risk of sinkhole occurrence or intensification will be analysed. It will be examined whether flooded mines are located in areas prone to seismic activity, heavy rainfall, landslides, presence of faults or fracture zones, and extreme temperature changes.

To complement these tasks, we will develop a unified database with a hydrogeological - geological classification and analysis of the terrain flooding studies, and we will add the development of a set of standards to classify mining areas exposed to risks, depending on the economic activities of the surrounding areas.

The creation of the database can be carried out using tools such as Microsoft Excel and Geographic Information Systems (GIS), by combining the capacity of data management and spatial analysis.

The information will be structured in Microsoft Excel tables, with rows and columns that organise data such as identifiers, attributes and descriptions, facilitating calculations and filters. In parallel, this information must be graphically represented in GIS software, where the data is linked to specific geographic locations. This will allow to visualise, analyse and manage the data in a spatial context, integrating maps with descriptive attributes. The synergy between Excel and GIS not only optimises the organisation of data, but also enhances its interpretation by combining precision data management with dynamic visual representations.

In order to estimate the response of the surface and to understand the spatio-temporal evolution of the hydro-mechanical phenomena and hazards of the mines, the next numerical simulation will be developed:

A first geological model will be created in Leapfrog 3D composed of the geological body, surface uplifts or subsidence, mine workings, fractures and discontinuities, geomechanical behaviour and hydraulic data.

To continue with the development of the numerical model, Systra Subterra will use FLAC3D software, a tool designed for the analysis of continuous media in geotechnical engineering. This numerical simulation will allow modelling and simulation of the mechanical and hydromechanical behaviour of the materials present in the Kazimierz Julius area, providing a detailed understanding of the interactions between stresses, deformations and fluid flow in the subsoil. Through this numerical approach, the phenomena associated with the stability of underground structures and the response of the ground to different loading and hydraulic pressure conditions will be analysed.

BRGM will carry out the numerical analysis using the 3DEC software of the French THIL site. 3DEC is a tool specialised in the simulation of discontinuous media using the discrete element method. This software is useful for modelling the mechanical behaviour of the rock matrix and the fractures that cross the subsurface, allowing a realistic and accurate representation of the processes occurring in terrains with significant structural discontinuities.

At the THIL site, the use of 3DEC will allow the simulation of how fractures and rock blocks interact under different loading and stress conditions, providing a comprehensive view of the geomechanical response of the terrain. This analysis will be the key to understanding the influence of fractures on rock mass stability and fluid flows, which are critical for the safe design and management of underground structures in the area.

The workflow for carrying out the simulations will be as follows:

1. Mechanical Simulation, to assess the impact of falling roofs on underground galleries in abandoned mines.
    - Construction of an initial geomechanical model representing the characteristics of the rock mass and the galleries.
    - Definition of the mechanical properties of materials (strength, elasticity, cohesion, etc.).
    - Application of loading conditions and simulation of possible structural failure scenarios, such as roof and wall collapses.
    - Generation of results on stress and deformation distribution.

2. Hydromechanical simulation, to analyse the effect of hydraulic disturbances on mine stability and their interaction with mechanical processes.
    - Incorporation of hydraulic parameters into the model, such as permeability, pore pressure and water flow.
    - Simulation of seepage, water accumulation and changes in hydrostatic pressure conditions.
    - Study of how hydraulic variations affect the mechanical behaviour of the terrain, especially in fractured or weakened zones.
    - Assessment of the risks associated with collapse induced by these interactions.

3. Sensitivity analysis, with the aim of identifying the most influential parameters of the model in the appearance of sinkholes and prioritising the critical factors in the predictive design.

- Systematic variation of key geomechanical parameters (rock strength, hydraulic properties, geometry of the galleries).
- Simulation of different scenarios to observe the sensitivity of the model to variations in these parameters.
- Evaluation of the surface response, especially the formation of sinkholes or ground deformations.
- Identification of critical parameters that require greater precision in their characterisation to improve the predictivity of the model.

4. Comparison with InSAR analysis generated in WP4 task 4.2 by the BRGM, with the aim of carrying out a comparison of spatio-temporal maps of land surface movements to validate the numerical models for the site, based on the INSAR technology.

One of the expected results will be the identification of precursor signals in the response of the surface to critical hazards and to know which key parameters must be monitored and controlled to prevent collapse and undermining.

In parallel, analyses will be carried out at IMG PAN in connection with the development of FEM geomechanical models, initially created in the previous projects I2MON and MERIDA, to describe ground surface movements during the flooding of underground mines. Researchers have created models that have been applied in several mining regions in Germany, Spain and Poland. As experience shows, the models are highly effective in predicting maximum deformation indicators. However, despite numerous FEM modeling works in this area, obtained results do not confirm the observed range of influence during mine flooding on the land surface. The researchers of IMG PAN will focus their numerical analyses on this issue.

Related documents:
Milestone 3 – Numerical Model (IMG-PAN) 30.06.2026

5.2.4. WP4. Sinkhole hazards and risks related to shallow mine workings

WP Leader: BRGM, Participants: GIG-PIB, INERIS, DMT-THGA, IMG-PAN, SUBTERRA.

Main goals of WP4:

- Development of operational tool for predicting sinkhole hazards
- InSAR analysis of selected test sites
- Study of the consequences of ground movements (subsidence, sinkhole, uplift, etc.) on structures and infrastructures (buildings, buried pipelines, etc.) by considering Soil-Structure Interaction (ISS)
- Development of fragility functions, which will express the probability of structural damage or malfunction for a given level of ground deformation.
- Implementation and run of risk assessment workflows in the VIGIRISKS platform (BRGM).

WP4 will involve in-depth data analysis with particular focus on estimating the risk associated with the formation of sinkholes in post-mining areas. Using the database information in selected European coal basins (WP2), the analysis will consider the quality, the heterogeneity, the absence of the information. Work will be undertaken to identify the main factors determining the formation and the occurrence of sinkholes using numerical methods (e.g. the Mont-Carlo simulation). This risk assessment will be driven on the defined testing sites on the basis of WP3 numerical simulation model results reproducing the deformation due to underground sinkholes. InSAR technology will provide analysis of Earth surface displacement from satellite imagery and will therefore contribute to the validation and interpretation of the modelled ground deformation maps, which will be used as the hazard input data taken into account for the risk assessment method. This work will lead to the development of an operational method resulting in the form of a map estimating damages and losses to technical and construction infrastructure in the analysed post-mining area.

The Work Package has been divided into four tasks, a detailed description of each task is presented below.

Task 4.1. Operational tool for predicting of sinkhole hazard related to shallow mine workings

Task Leader: SUBTERRA; Participants: INERIS

Goals:

- development of operational tool for predicting sinkhole hazards,
- identification the main factors of the occurrence of the sinkhole.

A probabilistic study on sinkhole formation will be carried out. in this study the two areas to be analysed will be: the water level (groundwater level) and the properties of the rock massif. This rock mass is characterised on the basis of the definition of the rock matrix, which is the lithology, and on the basis of the frequency and orientation of the discontinuity planes.

Starting from the databases already created in WP2 and completing them, if necessary, a database that perfectly reflects the mechanical behaviour of the rock massifs will be created, for which the following factors will be analysed:

- rock matrix: lithology (petrographic characteristics and properties)
- Discontinuities: fracturing (type and frequency)
- non-discontinuous geological structures (sedimentary, tectonic: folds...)
- Natural stresses (tensional or stress state, seismicity, movements...)
- Geo-environmental factors: - degree of weathering, susceptibility to weathering
- Hydrogeological conditions (water table and its variations, moisture content, water circulation).

The effect of natural factors will be also considered and man-made works, such as mining works that have taken place in each area. The following factors related with the mining works will be considered: method of exploitation used, angle of influence, power of the layer, lithology through which the exploitation passes, width and depth.

With the analysis of the created database, it will be possible to carry out an in-depth statistical - probabilistic study that will allow to identify and relate the developing factors and the factors that trigger the appearance of subsidence and landslides.

Ineris will carry out a comprehensive identification of the key factors driving the occurrence of sinkholes, focusing on shallow coal mines across Europe. This will involve a systematic, in-depth analysis using advanced database processing and statistical techniques. The study will address critical challenges such as data quality, the heterogeneity of datasets, and gaps or missing information that are common in this domain.

To enhance the robustness of the analysis, additional investigations will include sensitivity-based parametric studies relying on analytical and numerical mechanical calculations. This analytical model, developed by Ineris, allows model to predict the height of sinkhole propagation. It is based on the assumption that the phenomenon is halted by self-filling, resulting from the bulking of collapsed materials. Several parameters play a critical role in the expected chimney propagation height. These include, in particular, the chimney radius, the bulking factor of the collapsed materials, and the angle of repose of the debris. The approach involves a three-dimensional volumetric modeling of the void to be filled within underground workings. Different formulations can be used depending on the mining method implemented in the underground operations (e.g., abandoned room-and-pillar workings, various gallery shapes). Based on available information regarding the geometry of the workings and the properties of the overburden materials, the model enables the determination of the expected chimney propagation height. This, in turn, allows for an assessment of the risk of sinkhole emergence at the surface.

These studies will aim to quantify the impact of key variables and their interactions. Specifically, Ineris plans to employ methods such as the Monte Carlo simulation to explore the role of parameters that are difficult to measure or entirely unmeasured, like the buckling factor, pore pressure variations, and soil layering effects.

The analysis will also incorporate advanced probabilistic approaches to assess the uncertainties associated with different data sources and model assumptions. By combining statistical techniques with expert judgment, the methodology will refine the prediction of sinkhole hazards. This will include integrating geological, hydrological, and mechanical factors, as well as valuating the spatial and temporal patterns of sinkhole occurrence.
The expected outcome of this task is an operational methodology to predict both the likelihood and severity of sinkhole hazards.

With the objective of being able to predict, through the tool, when and under what conditions sinkholes occur and if there is a risk of them occurring.

Related documents:
Deliverable D4.2 – Operational tool for predicting of sinkhole hazard 30.09.2026

The development of the work proposed to be able to implement the tool is as follows:

Work plan
1) Database creation – Database analysis (M1 – M26)
2) Numerical model results analysis (M12 – M26)
3) Tool development (M1 – M19)
4) Data ingestion into the tool (M19 – M26)
5) Elaboration of the deliverable D4.2 (M24 – M26)

Task 4.2. Monitoring of land surface motion based on advanced satellite InSAR

Task Leader: BRGM; Participants: GIG-PIB, DMT-THGA

Goals:
- comprehensive monitoring of land surface motion based on advanced satellite InSAR technologies to map the spatio-temporal variability of land surface movements,
- establish links with groundwater level changes,
- evaluate the impact of mine flooding processes on surface instability,

- implement forecasting models to quantify the progression of surface motion for numerical simulations,
- compare and validate ground motion models generated in WP2 task 2.3. If possible, definition of early warning signs.

Comprehensive monitoring of land surface motion based on advanced satellite InSAR technologies to map the spatio-temporal variability of land surface movements. Establish links with groundwater level changes, Evaluate the impact of mine flooding processes on surface instability, Implement forecasting models to quantify the progression of surface motion for numerical simulations, Compare and validate ground motion models generated in WP3 task 3.3, If possible, definition of early warning signs.

InSAR technology will provide analysis of material from satellite imagery and will therefore contribute to the validation and interpretation of the modelled ground deformation maps, which will be used as the hazard input data taken into account for the risk assessment method. For this task, imagery from the Sentinel 1 mission will be used. The imagery made available since 2014 free of charge through the European Space Agency's Copernicus programme. The potential of the Copernicus Sentinel 1 mission is evidenced by its ability to simultaneously tracking or monitoring ground surface displacements, to a very high precision, in areas up to approximately 48 000km^2 (270x270 km - this is Sentinel 1 swath width) 2 with an interval of 6 or 12 days (depending on the satellite mission use duration of operation)., We will taking take into account the well-known limitations of the InSAR approach (e.g. possible loss of signal coherence in highly vegetated areas)making it - for instance - inefficient in forest areas. And more appropriate for slow, regular movements than fast, sudden ones). Moreover, SAR signal it is a radar satellite whose signal allows penetrates the action of cloud cover – allowing operation data acquisition independently of the weather conditions and, since SAR is an active system, day/night data acquisition salternation. So this aspect is completely negligible. In addition, TerraSAR-X technology satellite data will be requested on research purposes to use higher resolution data (1 meter resolution).

A first step will be to define and select the study sites, in addition to Thil site and Kazimierz Juliusz site, based on available data from WP2 database, knowledge of existing sites. The second step will be to define the temporal period on which the monitoring should be done based on historical sinkhole phenomenon or ground movements. Then, the definition of the needed and wanted resolution depending on the available and free or low-cost data accessible in the allotted time. Deliverable D4.1 redaction will start mid-2025 when the methods will be fully established and the monitoring begun. Depending on the preliminary results in 2025, links between land surface motion and groundwater level changes (T3.3) will attempt to be established and a comparison and validation of ground motions models generated in T3.3 will be done. An attempt to define early warning signs will be made if the InSAR results allow it. Towards the end of the project, interferometric results will be created to be implemented in T4.4 risk assessment.

Related documents:
Deliverable D4.1 – Presentation of the method and 1st results of the interferometric processing phase on the identified site of Thil (France)
31.12.2025

Task 4.3. Study of the consequences of ground movements on structures and infrastructures

Task Leader: UL; Participants: BRGM

Goals:

- study of the consequences of ground movements (subsidence, sinkhole, uplift, etc.) on structures and infrastructures (buildings, buried pipelines, etc.) by considering Soil-Structure Interaction (ISS),
- numerical modelling.

Study of the consequences of ground movements (mainly sinkholes) on structures and infrastructures (buildings and buried pipelines) by considering Soil-Structure Interaction (ISS). This phenomenon considers the rigidity of the ground and that of the structure to better assess the deformations transmitted to the structure and their consequences (malfunctions or damage). The study will be based on numerical models which themselves are validated through physical and analytical modelling and also through the data base of numerous observations of ground movements realized in different European basins (in this task we will use the information provided by WP.2). Moreover, for validation of the models, it might be possible to benefit from the monitoring designed by the partners in the Task T2.4. BRGM will participate in the discussion on the design of experiment and select the optimal way to monitor the test sites of the project, in order to reflect engineering needs. The numerical models will enable us to study certain mitigation strategies, so that we can eventually make practical recommendations if the simulations are meaningful and allow such conclusions. The potential impact of these hazards will be quantified though vulnerability curves, which will express the probability of structural damage or malfunction for a given level of ground deformation.

Related documents:
Milestone 4 – Draft result – deliverable of preliminary models 28.02.2026

Task 4.4. Risk analysis of built infrastructure

Task Leader: BRGM; Participants: UL

Goals:

- Implementation and run of risk assessment workflows in the VIGIRISKS platform (BRGM).

This task pertains to the risk analysis of built infrastructure, including common buildings and infrastructure systems (roads, buried pipelines) through the combination of deformation fragility functions (interaction with T4.3) and hazard assessment (interaction with T3.3 and T4.2). It is planned to use pre-existing risk assessment workflow structures (e.g., landslide risk from InSAR hazard detection) to be adapted to the sinkhole phenomenon. Implementation and executions of these new adapted risk assessment workflows will be carried out in the VIGIRISKS platform (https://vigirisks.fr) developed by BRGM. VIGIRISKS is a scientific platform facilitating the provision, traceability and execution of calculations, treatments and modelling in the field of natural risks (Negulescu et al., 2022). Risk assessment results will be given through the form of a quantification of building damage and loss maps across a given area, while accounting for infrastructure damage. If available, the possibility of including data from monitoring task T2.4 in the risk assessment, whether for buildings or infrastructure, can be studied.

At first, it will be necessary to define and select the study sites based on available data (database of WP2) and knowledge of the sites. Afterwards, the collection of needed data such as asset exposure (building, infrastructure system, networks, population…), vulnerability (building types, definition of fragility functions based on T4.3 numerical models) and hazard (hazard assessment definition through historical sinkhole event study based on T4.2 related to InSAR and T3.3 related to numerical models on surface response around flooded abandoned mines) is mandatory. Next step will be the adaptation of existing risk assessment workflow structures to make them operational on sinkhole risk assessment. These workflows will then be ready for implementation and execution through the VIGIRISKS platform on the previously defined study sites. Compilation of results through loss maps expressing potential damages to common buildings and infrastructure systems will be the last step before writing-up the deliverable report D4.4.

Related documents:

5.2.5. WP5. Machine learning modelling

WP Leader: IMG-PAN, Participants: GIG-PIB.

Main goals of WP5:

- development of a methodology for automatic data aggregation,
- determining the risk factors for sinkholes,
- development of a prediction model for sinkhole occurrence.

Simultaneously to work in WP4, advanced research will be carried out using Machine Learning (ML) and Deep Learning (DL) methods. During this work, scientists from IMG PAN will obtain data characterizing selected areas and, based on expert knowledge, collect information on factors and phenomena affecting the possibility of discontinuous surface deformations. These data will be supplemented with the results of work carried out in parallel in WP2, WP3 and WP4. The materials obtained in this way will allow the creation of structured databases. Creating them will require developing a methodology for automatically aggregating attributes and combining them into coherent data sets. For this purpose, existing database architectures and Big Data techniques will be used. If there are not enough cases, it is intended to expand the existing data sets (data augmentation) using numerical and statistical methods. This will increase the efficiency, reliability and accuracy of ML/DL models. The database developed in this way will allow in subsequent stages to build a training model dedicated to ML. One of the stages of WP5 will be tuning the model parameters and validating the obtained results in order to select the optimal one, and then comparing the machine learning results with the results presented in WP3 and WP4. Artificial intelligence (AI) techniques are being incorporated into broader initiatives focusing on the assessment and monitoring of geological hazards, an example of which is their use in earlier RFCS projects (IMPRESS) or EU Horizon 2020 Projects (ITN IGNITE, LANDSLIP, CERBERUS, FLUIDGLASS) as well as the financed from other sources, the Italian SISMA project. Although sinkhole analysis is not always the primary focus of these projects, the ML and DL methodologies and technologies developed within them can provide valuable insights and tools for sinkhole hazard assessment and risk management in post-mining areas and other susceptible regions.

Task 5.1. Data analysis, pre-processing and engineering

Task Leader: IMG-PAN; Participants: GIG-PIB

Goals:

- data analysis of databases form T2.1 and T2.2.

This task aims to bring together data generated within WP2, WP3, and WP4 to build a relevant training set dedicated to the machine learning task (T5.3). Considering the heterogeneous nature of the data, a dedicated methodology to automatically aggregate and merge them should be developed. Relevant data will be selected regarding the results of their statistical exploration and recommendations of experts on sinkhole risks.

The process will focus on selection of the applicable data using among others filter methods, wrapper methods, and embedded methods, data integration by means of merging the dataset, creating new features/attributes, data cleaning, and filtration of relevant information. In the next steps, the elimination of existing outliers, and treating the lacking values through either eliminating them or imputing them, treating inaccurate data by eliminating them, will be executed.

The final step will be based on the examination of the data by formulating the various statistical functions. Identifying dependent and independent variables or features will be performed and finally the analysis of key features of data to work on.
Results will be given in the form of a dataset.

Task 5.2. Data augmentation

Task Leader: IMG-PAN; Participants: GIG-PIB

Goals:

- data analysis using ML/DL,
- development of a methodology for automatic data aggregation.

This task will focus on extending the dataset to improve the performance of the model. Advanced computer processing techniques will be used to generate additional records from the original data. On the other hand, synthetic data will be generated using numerical modeling (FEM) and statistical techniques (e.g. Monte Carlo Simulation) to ensure properly balanced data sets.

Task 5.3. Modeling the possibility of discontinuous deformation hazards in the form of sinkholes using machine learning techniques and validation process

Task Leader: IMG-PAN; Participants: GIG-PIB

Goals:

- development of a prediction model for sinkhole occurrence.

The process of developing different kinds of classification models (machine learning and deep learning) in order to select the proper one, which in the best way will predict the possibility of sinkholes. After deciding on the model family, amongst the number of algorithms in that family, there is a need to cautiously pick out the algorithms to put into effect and enforce them. The next step is to tune the hyperparameters of every model to obtain the preferred performance. Additionally, there is a need to make sure that the final model has the right stability between overall performance and generalizability. For this purpose, model evaluation and validation will be done.

Related documents:
Milestone 6 – Machine learning model for sinkholes 30.06.2026

<u>Task 5.4. Comparing ML/DL models performance on real data</u>

Task Leader: IMG-PAN; Participants: GIG-PIB

Goals:

- determining the risk factors for sinkholes,
- development of a prediction model for sinkhole occurrence.

The process in which the model is evaluated to check if it is ready to be deployed. The model is examined on unseen data and evaluated on a cautiously thought-out set of assessment metrics. There is additionally a need to make sure that the model conforms to reality. If the proper quality end result in the evaluation is not achieved, we have to re-iterate the complete modelling procedure until the preferred level of metrics is achieved. The model assessment will help to select and construct the best possible model. Additionally results of the T5.3 will be compared on-going with existing risks/hazard maps and results from WP2.

Related documents:
Deliverable D5.1 –Risk analysis of built infrastructure 31.03.2027

5.2.6. WP6. Valorisation, dissemination and exploitation of the results.

WP Leader: DMT-THGA, Participants: GIG-PIB, INERIS, BRGM, IMG-PAN, SUBTERRA, UL, GEODERIS.

Main objectives of WP6:

- development of the Decision Support System,
- electronic publication of guidelines,
- publication of 3 peer-reviewed papers,
- 3 presentations at scientific conferences.

This WP is the last step of the SIRIMA project implementation. The main tasks of this WP are based on controlling and strengthening the dissemination of the SIRIMA project among different stakeholders. This will be achieved by, among others, using a spatial Decision Support System (DSS) for the management of the sinkhole risk in European coal basins integrating social and economic aspects. A decision support system (DSS) is an information system that supports business or organizational decision-making activities. DSSs serve the management, operations and planning levels of an organization (usually mid and higher management) and help people make decisions about problems that may be rapidly changing and not easily specified in advance - i.e., unstructured and semi-structured decision problems. Decision support systems can be either fully computerized or human-powered, or a combination of both.

Other ways of disseminating the project will include publications, presentations at conferences, preparation and making available in the public space through online tools, a guide on the sinkhole hazard in post-mining areas.

Task 6.1. Development of SDSS (spatial Decision Support System) – GIS based, webbased GIS

Task Leader: DMT-THGA; Participants: GIG-PIB INERIS, BRGM, SUBTERRA, UL.

Goals:

- development of the Decision Support System.

The DSS will allow to implement risk assessment methods with the aim to be a tool for risk management and decision:

- identifying the DSS specifications, compile and analyse the DSS objectives, functional and non-functional requirements, and the restraints on the DSS development, use and evolution.

Defining DSS objectives in this Task will include clarifying the usage of the DSS; the type of decision outcome(s); and the decision-making level the DSS will support. The uses envisaged for post-mining multi hazard management DSS will include:
(i) identifying the realistic management choices;
(ii) integrating information into a coherent framework for analysis and decision-making discerning key information and impacts decision-making from more basic information; and
(iii) providing a framework for transparency (i.e. all parameters, assumption, and data used to reach the decision are clearly demonstrated). Functional requirements will be defined for the DSS operational functionalities, they will depend on the role of DSS in meeting the decision objective(s) and on technical objective(s) of the DSS.

Related documents:
Milestone 3 – DSS requirement 31.12.2025
Deliverable D6.1 –DSS 28.02.2027

Task 6.2. Development of general rules of conduct to reduce the sinkholes risk in closured mines and protection of buildings and critical infrastructure

Task Leader: DMT-THGA; Participants: All Partners

Goals:

- systematization of knowledge and data collected during the project implementation,
  - preparation of a guide on the sinkhole hazard in post-mining areas. Guideline (short and clear) for the management of the coal region in transition.

The guideline will contain instructions for the uniform and efficient engineering and mining handling of sinkholes that are relevant to damage. The differentiated mining measures are used to ensure safety, in particular depending on the use of the surface. The document will deal with measures to ensure minimum standards in the performance of detection, assessment and remediation as well as monitoring of areas related to sinkhole hazards.

Related documents:
Deliverable D6.2 – Guideline 30.04.2027

Task 6.3. Publications and dissemination of research results by participation in industry and scientific conferences.

Task Leader: DMT-THGA; Participants: All Partners

Goals:

- Publication of 3 peer-reviewed papers,
- 3 presentations at scientific conferences.

Results will be promoted in peer reviewed publications (3 papers) and on scientific conferences (3). For instance in Germany on the occasion of the NACHbergbauZeit, a conference organised by DMT-THGA and the mining authority in North Rhine-Westphalia every two years or on the Altbergbaukongress (old mining conference) which takes place every year at one of the mining of universities in Freiberg, Clausthal, Aachen, Bochum and Leoben (Austria).

6. Summary

Mining is one of the basic activities carried out by humans during their development over thousands of years. The industrial revolution in the 18th century caused a huge increase in demand for basic energy resources (coal) and industrial raw materials (metal ores). As a result, mining of these deposits developed, first opencast and over time deep mining. Over the centuries, this activity has caused a huge transformation of the environment. Each mining plant extracting a deposit useful for humans causes, among other things: a change in the terrain, a change in water conditions and, above all, the drying of vast areas, numerous pollutions and mining damages. These processes, with varying intensity, occur during the period of mine operation and do not disappear in the last stage of activity, which is its liquidation. Liquidation of a mine usually occurs as a result of the depletion of the exploited deposit or the unprofitability of exploitation. In the distant past, the liquidation of a mining site consisted in abandoning it and leaving nature to a natural revitalization process lasting hundreds of years. Currently, the process of mine liquidation is an extremely complicated and expensive undertaking, and its effect should be the permanent minimization of the negative impact of the former mine on the environment. Additionally, due to the ongoing climate change, an important aspect during mine liquidation should be the restoration of natural aquifers. This process, due to the large amount of voids left after the mining operation, creates a risk of uncontrolled and sudden sinkholes.

The SIRIMA project is aimed at developing a procedure for mine closure and the possibility of flooding it in the event of uncontrolled movements of the surface of post-mining areas (sinkholes).

7. References (previous projects, publications)

The SIRIMA Project is associated with the following Research Fund of Coal and Steel (RFCS) Programme projects:

- RFCR-CT-2003-00006: Optimization of mine water discharge by monitoring & modelling of geochemical processes & develop. of measures to protect acquifers & active mining areas from mine water contamination (WATERCHEM). Project duration: 2003 –2007.
- RFCR-CT-2008-00005: Flooding management for underground coal mines considering regional mining networks (FLOMINET). Project duration: 2008 –2011.
- RFCR-CT-2013-00005: Management of mine water discharges to mitigate environmental risks for post-mining period (MANAGER). Project duration: 2013 –2016.
- RFCR-CT-2014-00001: Low-Carbon After-Life: sustainable use of flooded coal mine voids as a thermal energy source - a baseline activity for minimising post-closure environmental risks (LoCAL). Project duration: 2014 –2017.
- RFCR-CT-2010-00014: Mine shafts: improving security and new tools for the evaluation of risks (MISSTER), Project duration: 2010-2013.
- RFCR-CT-2015-00002: Long-term Stability Assessment and Monitoring of Flooded Shafts (STAMS). Project duration: 2015 – 2018
- RFCS-CT-2012-00003: Complex mining exploitation: optimizing mine design and reducing the impacts on human environment (COMEX), 2012-2015.
- RFCR-CT-2015-0004: Management of Environmental Risks during and after mine closure (MERIDA), Project duration: 2015-2019.
- Grant Agreement No 899278: The impact of extreme weather events on mining operations (TEXMIN). Project duration: 2019 – 2022.
- EIT Raw Materials KAVA 6: Revitalising Post-Mining Regions: Problems and Potential in RIS Europe (REVIRIS). Project duration: 2020 – 2021.
- RFCS-Grant Agreement No 800689: Integrated Mining Impact Monitoring (i2MON) Project duration: 2018 – 2022.
- RFCS-Grant Agreement No 899278: Transition Information Modellig for Transition from Coal Exploitation to a Re-Vitalized Post-Mining Landscape (TRIM4POSTMINING) Project duration: 2020 – 2021.
- RFCS-Grant Agreement No 899278: Induced earthquake and rock mass movements in coal post mining areas: mechanisms, hazard and risk assessment (POSTMINQUAKE). Project duration: 2020 –2023
- RFCS-Grant Agreement No 101057326 Post-mining Multi-hazard evaluation for land-planning (POMHAZ). Project duration: 2022 –2025

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