PoMHaz

Post-Mining Multi-Hazards evaluation for land-planning

PoMHaz

WP5: Application on real case studies

D16: Deliverable 5.1 - Requirements of end-users and risk criteria for abandoned sites

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Acronyms

CERTH	The Centre for Research & Technology, Hellas
PIG-PIB	Polish Geological Institute – National Research Institute
PPC	Public Power Corporation S.A.
RFCS	Research Fund for Coal and Steel
THGA	Technische Hochschule Georg Agricola
WUG	Coal Mining Authority

Executive Summary

This deliverable is part of the POMHAZ project, Post-Mining Multi-Hazards evaluation for land-planning. The main objective of POMHAZ is to identify the interaction between the post-mining hazards for coalmines in Europe and to develop tools for facilitate the management of the post-mining hazards in coal region.

In the POMHAZ project, the present deliverable is part of the WP5 that is dedicated to the application of the tools (DSS and GIS) on European real case studies to test and validate the methodology and the tools (DSS and GIS). Therefore, Deliverable 5.1, is directly related to Task 5.1 “ End-user requirements and data collection”. This deliverable focuses on identifying end-user requirements and defining risk criteria for post-mining areas. The overarching objective of WP5 is to validate the GIS and Decision Support System (DSS) tools developed in earlier project stages by applying them in real post-mining environments across four European countries: Poland, France, Germany, and Greece. These locations represent diverse geological, mining, environmental and socio-economic settings, enabling comprehensive evaluation of the tools' flexibility, applicability, and effectiveness.

The work undertaken included: collection and harmonisation of detailed geological, hydrological, mining and environmental datasets; identification and prioritisation of relevant hazards; consultation with local end-users including municipalities and mining authorities; and formulation of requirements for data input and system functionalities. End-users expressed the need for intuitive tools supporting spatial planning, early hazard identification, and communication of risks to decision-makers and the public. Key requirements included high-resolution GIS layers, integration of historical mining data, capability to model hazard interactions, and visualisation functions enabling transparent and informed decision-making.

Case studies included three post-mining cities in Poland (Sosnowiec, Piekary Śląskie, and Wałbrzych), the lignite basin of Peypin in France, the Megalopolis lignite mines in Greece, and the southern Ruhr region in Germany. These sites differ in mining legacy (deep and shallow mines, open-pit operations), chronology of closure, natural conditions, and intensity of hazards. Across the sites, common post-mining hazards included ground subsidence, sinkholes, surface deformation, hydrological disturbances, gas emissions (particularly radon), spontaneous combustion of waste material, and environmental pollution. Natural hazards often coexist and interact with mining-induced risks, such as seismicity, landslides and flooding, increasing the complexity of risk assessment.

The analysis revealed substantial differences in hazard intensity: Polish and German cases are characterised by widespread subsidence and sinkhole risk due to extensive historical underground workings, whereas the French and Greek sites show more scenarios involving slope movement and interaction between natural and mining-induced hazards. The ability of the GIS-DSS tool to accommodate these variations demonstrates its versatility and suitability for diverse post-mining environments.

Work carried out in this task confirmed the need for accurate and continuous data input from local authorities, mining operators and geological services. Pilot testing highlighted the importance of user-friendly interfaces, clear hazard classification, and inclusion of long-term forecasts, particularly in areas undergoing mine flooding and hydrogeological rebalancing. The output of this deliverable forms the basis for full-scale validation of the PoMHaz system by end-

users, guiding operational improvements and further development of hazard assessment methodologies.

In summary, Deliverable D16 successfully defines the technical and operational requirements for end-users and identifies key hazard criteria essential for sustainable management of post-mining regions. The results demonstrate that the PoMHaz GIS-DSS has strong potential to support integrated land-use planning, risk mitigation and safe redevelopment of post-mining territories across Europe. The insights gained establish a robust foundation for subsequent tool testing and adoption, supporting long-term environmental safety and socio-economic revitalisation in regions transitioning from coal-based economies.

1. Background

The general objective of WP5 was to validate the usability of the tool (DSS and GIS) developed in the previous tasks for multi-hazards management on real case studies. It was necessary to apply tools, prepared already within the project in real conditions of four different sites from Poland, France, Germany and Greece. Every site has its own specific requirements and characteristics; therefore, it was essential to achieve the flexibility of the proposed tools. The main objectives were:

- To check end-user requirements in terms of GIS and DSS;
- To prepare dedicated tools, supporting the decision making in spatial planning;
- To identify the requirements of all partners – both partner towns and the SRK company, due to their long-term plans of town development, environmental conditions, the level of the infrastructure (technical, construction etc.), urban features (dense, dispersed buildings);
- To prepare dedicated GIS and DSS tools, based on the collected detailed data and requirements, formulated by the end users / administrators of the selected test sites;
- To provide required data to test GIS and DSS;
- To provide end users requirements in terms of GIS and DSS.

To achieve the objectives of the WP5, the following work was done:

- Preparation of detailed data specific to case studies (Poland, France, Germany and Greece), necessary to create the GIS and DSS input. Data was collected, or additional tests were carried out at each place, e.g. gas emissions (including radon), parameters of subsidence in basins.
- Description of the state of hazards / phenomena such as subsidence, changes in hydrogeological conditions, gas emissions, including radon;
- Long-term forecasts of changes in the range and intensity of individual hazards (GIS, DSS);
- Description of correlation between these phenomena;
- Verification and validation of prepared tools in real conditions;
- Joint testing of the tools with end-users and analysis of method limitations resulting from a possible inability to meet GIS and DSS requirements.

Description of the Deliverable D16 (5.1)

As a part T5.1., all Project Partners prepared deep analyses of selected study areas:

- In Poland, 2 cities for Upper Silesian Coal Basin and 1 city representing Lower Silesian Coal Basin were chosen.
- In France, area of Peypin post ming site was selected.
- In Germany, case study is located in North-Rhine-Westphalia of the Ruhr area.
- In Greece, Megalopolis lignite mine area has been analysed.

The selection of locations shows how post-mining areas differ in terms of geological structure, environmental and technical conditions. However, each of the sites presented has problems, hazards and risks caused by natural and mining factors. Thanks to its versatility and flexibility, the developed GIS DSS tool can support and indicate development opportunities for all areas.

2. The selection of cities as a well-known historical case studies

2.1. Poland

GIG-PIB proposed three partner-cities located in different parts of Poland – see Figure 1.

1. Wałbrzych – coal mines closed about 20 years ago, mixed types of buildings,
2. Sosnowiec – the last mine was closed in 2016, since 2017 the process of flooding has begun, dense urban development,
3. Piekary Śląskie - mining activities are finished, last coal mine closed in 2020, partly rural area, dispersed buildings.

Based on the knowledge we had at the beginning of the task, thirteen hazards, potentially occurring in post-mining areas, were analysed. As many as 10 hazards were found to exist (or may occur) in Walbrzych. In Sosnowiec 7, while in Piekary Śląskie only 2 hazards are relevant (subsidence and sinkholes), while the others are insignificant or the probability of occurrence is negligible.

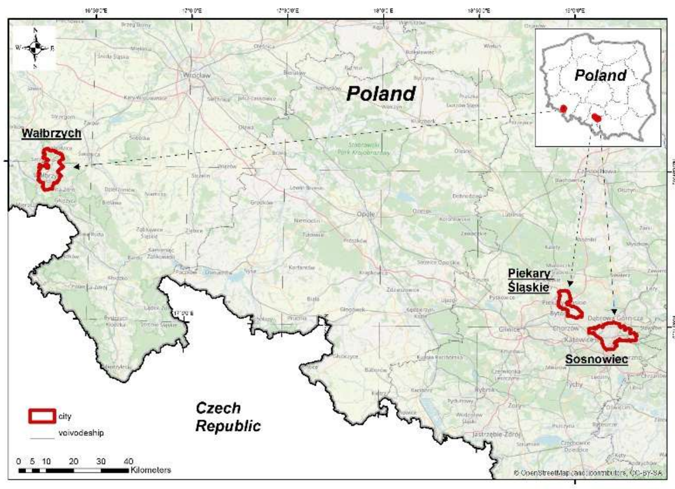

Figure 1: Location of Polish partner cities – real case study

In Poland, 3 investigation coal mining sites were chosen: Sosnowiec, Piekary Śląskie and Wałbrzych.

Sosnowiec is one of the central hubs of the Upper Silesian conurbation, located in the southern part of Poland, on the Silesian Upland, which is part of the Silesian-Cracow Upland, in the central area of the Upper Silesian Industrial District. The city covers an area of approximately 91 km^2. Coal mines had been operating since the 19th century, with the last one being closed in 2021.

Piekary Śląskie is located in the southern part of Poland, in the Silesian Upland, within the Upper Silesian conurbation. The city lies in the central area of the Upper Silesian Industrial District, part of the Silesian Voivodeship. It is situated close to other major cities in the region, such as Katowice and Sosnowiec. The city is located in the northern part of the Silesian Upland. Currently, no coal mines operate within the city's boundaries, and some of the post-mining areas have been revitalized.

Wałbrzych, the most important city of the Walbrzych Basin, is situated in the south-western part of Poland. It is surrounded to the north by the Wałbrzyskie Mountains with part of the Trójgarb Massif and the Chełmiec Massif. The mining area of the Wałbrzych region, with an area of 94 km^2, is located in the mid-mountain depressions of the Central Sudety Mountains. Walbrzych, with its extensive mining infrastructure, is undoubtedly a testimony to the process of industrialisation that took place in the 19th and 20th centuries in Europe, and the architectural and technical qualities of some of the buildings are worthy of preservation.

2.1.1 Geological information

Sosnowiec

Sosnowiec is located in the north-eastern part of the GZW. The crystalline bedrock of the area (located within the Western European platform) is composed of crystalline (magmatic and metamorphic) rocks of the Precambrian, on which younger formations, representing the cover floor of the platform.

Overburden - often anthropogenic materials, used for reclamation and backfilling e.g. shafts.

Quaternary – thickness up to 80m, represented by variously grained sands, silts and river silts. The Pleistocene is developed as fluvioglacial deposits, sands, gravels and glacial till. Triassic sediments lie unconformably directly on top of the Carboniferous. Represented by weakly compacted sandstones, fine- and medium-grained sands, grey and cherty siltstones. The Upper Sharp Sandstone is developed as marls and dolomitic limestones.

Upper Carboniferous formations are represented by sediments of the paralic Namurian A and limnic series corresponding to Namurian B-C and Westphalian A and B. The Upper Carboniferous sediments are composed of sandstones, siltstones, mudstones, shales and conglomerates, within which there are insets and coal seams. In the formations of the Paralytic Carboniferous series in the Sosnowiec area there are also clay raw materials (montmorillonite), the most important of which are bentonites.

Coal deposits occur in several layers, varying in total thickness from 0,8m to 290m.

Piekary Śląskie

Overburden: usually Quaternary, in some areas, older geological formations (Triassic) create outcrops, without overburden.

Quaternary: represented by Holocene and Pleistocene deposits, sometimes reduced or with a thickness not exceeding a few meters.

Triassic: beneath the thin layer of Quaternary deposits lies a complex of Triassic formations, with a thickness reaching up to 160 meters. The layers are represented by marly dolomites, massive, only slightly porous, laminated spongy and cavernous ones with numerous voids.

Carboniferous developed in the form of alternating layers of siltstone, mudstone, sandstone and coal seams.

Wałbrzych

The geological structure of the area is complicated and complex as lithologically diverse rocks of Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian, Triassic, Cretaceous, Neogene and Quaternary age - represented by sedimentary, volcanic and metamorphic rocks - occur here.

Upper Carboniferous Namur AB-Stefan C: Upper Carboniferous sedimentary formations comprise overlying conglomerates, sandstones, siltstones and claystones with coal seams.

2.1.2 Mining methods, time of operation and hazards identified

Sosnowiec

In the 19th century mining depths did not exceed 40 m. The pillar-chamber mining system was used. The capacity of drainage system of underground workings was limited. In 1876 the modern deep mine Ludwig was founded, followed by Fanny Mine. Both mines mined at a depth of approx. 80 m. In 1888 the two mines were merged at a depth of 80 m and later at a depth of 280 m. The mining system in use at the time was pillar with roof collapse. After World War I, shallow mining was briefly resumed and developed. Hydraulic backfilling began around 1900. In 1925 longwall mining was introduced. From the interwar period onwards, hydraulic backfilling was used for about 50 years.

The hard coal mining started in the area of the city in 1806, when Hope Ludwig Mine was erected. The last one, Kazimierz Juliusz Mine was closed in 2015. So coal mining continued for 209 years.

Within the Sosnowiec area 6 mining hazards were identified:
- surface deformations,
- sinkholes,
- floodplains,
- environmental pollution from spoils,
- combustion of mine waste
- and ionising radiation (radon) emissions

Piekary Śląskie

In the past, since the Middle Ages locally zinc-lead ores have been exploited were mined using the open-cast method. In the 16th to 18th centuries, in addition to the open-pit method, a method using multiple shafts and tunnels was employed. Underground, contemporary methods: pillar mining with roof collapse, roof collapse using mechanized supports. Coal mining was carried out using various systems, including the scavenging, stripping and longwall systems. Mining reached depths from 120 m to 780 m, and the thickness of the layers extracted was from 0.8 m to 6.5 m.

The history of mining in Piekary Śląskie includes zinc and iron ore mining, which developed in the Middle Ages, and hard coal mining, which began at the end of the 19th century. Zinc and lead ore mining: Zinc and lead ore mining in this region dates back to the 12th century. Initially, deposits were mined at shallow depths, but from the 15th century onwards, drainage tunnels began to be dug, allowing access to deeper deposits. In the 18th century, the use of steam engines enabled further development of mining. The oldest coal mine, Radzionków Coal Mine operated since 1863 till 1975. The last one was Piekary Coal Mine (1999–2021). Coal mining continued for 185 years.

5 mining hazards were identified:
- surface deformations,
- sinkholes,
- floodplains,
- and ionising radiation: radon emissions
- hydrological disturbances.

Wałbrzych

In the past, from the mid-18th century, shafts up to a depth of 50 m and adits were excavated, and mining was carried out by means of galleries. After 1945, underground mining was carried out using the pillar and longwall system, mainly with roof caving, but also with dry and silt backfilling. In the final phase of the mines' operation, mining was carried out in protective pillars.

The greatest development of mining activity took place in the 19th century, when mining reached a depth of 110 metres. In the 20th century, the centre of mining shifted south, and mining continued until 1996, after which the mines were gradually closed down. Many shafts and small shafts remained, often with undocumented closure, posing a threat to the surface of the area. The oldest mine, Fuchs Mine started operation since 1770. The last one, Julia Mine was closed down in 1996. Coal mining continued in Lower Silesia Coal Basin for 226 years.

5 mining hazards were identified:
- surface deformations,
- sinkholes,
- floodplains,
- and ionising radiation: radon emissions
- hydrological disturbances

In addition to mining hazards, all of the analysed sites are also subject to natural hazards, primarily of a hydrological nature, related to, among other things, heavy rainfall, downpours and local surface water flooding. However, their effects, such as flooding, are largely inextricably linked to many years of mining activity, which has led to profound changes in the terrain, lowering or disrupting natural drainage profiles, and transforming river beds and drainage systems. In mountainous and foothill regions, such as Wałbrzych, natural topographical conditions also contribute to the occurrence of sporadic flash floods and flooding, as exemplified by the events recorded in Lower Silesia in 2024.

2.2.Peypin case study-France

Peypin is a town located 21 km from Marseille and 22 km from Aix-en-Provence in France (Figure 2), at an altitude of 307 m and its area is 13.35 km^2. The population of the municipality is 5600 inhabitants. The municipality has a relatively high density. The town is crossed by the A52 motorway, and several departmental roads (D7, D8, and D46A). There is an industrial activity zone with 73 companies. The municipality is in the lignitiferous basin of Provence.

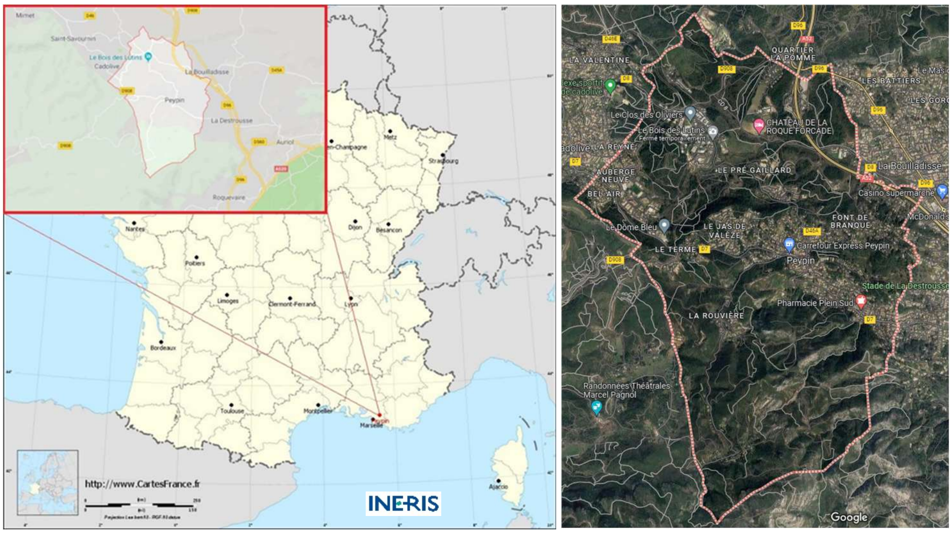

Figure 2: Location of the municipality of Peypin (13) - France

From the middle of the 15th century, the lignite basin was the subject of research authorization requests for coalstone or lignite. In the 20th century, Charbonnages de France (the national company for coal producing) became the holder of 16 Concessions (C1 to C16, covering most of the basin and 17 municipalities, Figure 3). The lignite was extracted using “rooms and pillars” and recently “longwall” mining methods. The depth of the mining works, under the town of Peypin, is between 0 and 800 m, with several shallow operations (0 – 140 m). In line with the lignite mines, there are underground cement stone quarries (mines) whose exploitation has enabled the development of the hydraulic lime and cement industry in the region of Peypin, Belcodène and La Bouilladisse.

The sector is located to the south of the Arc basin, to the north of the southern Provençal overlap, between the Chaîne de l'Etoile and the Massif de Régagnas. The outcropping formations are as follows:

- quaternary formations;
- the tertiary formations of the Stampien, which mainly extend in the southern part of the territory;
- the secondary formations of the Cretaceous contain at the top clays and marls, alternating with gray limestones and breccias of the Bégudien.

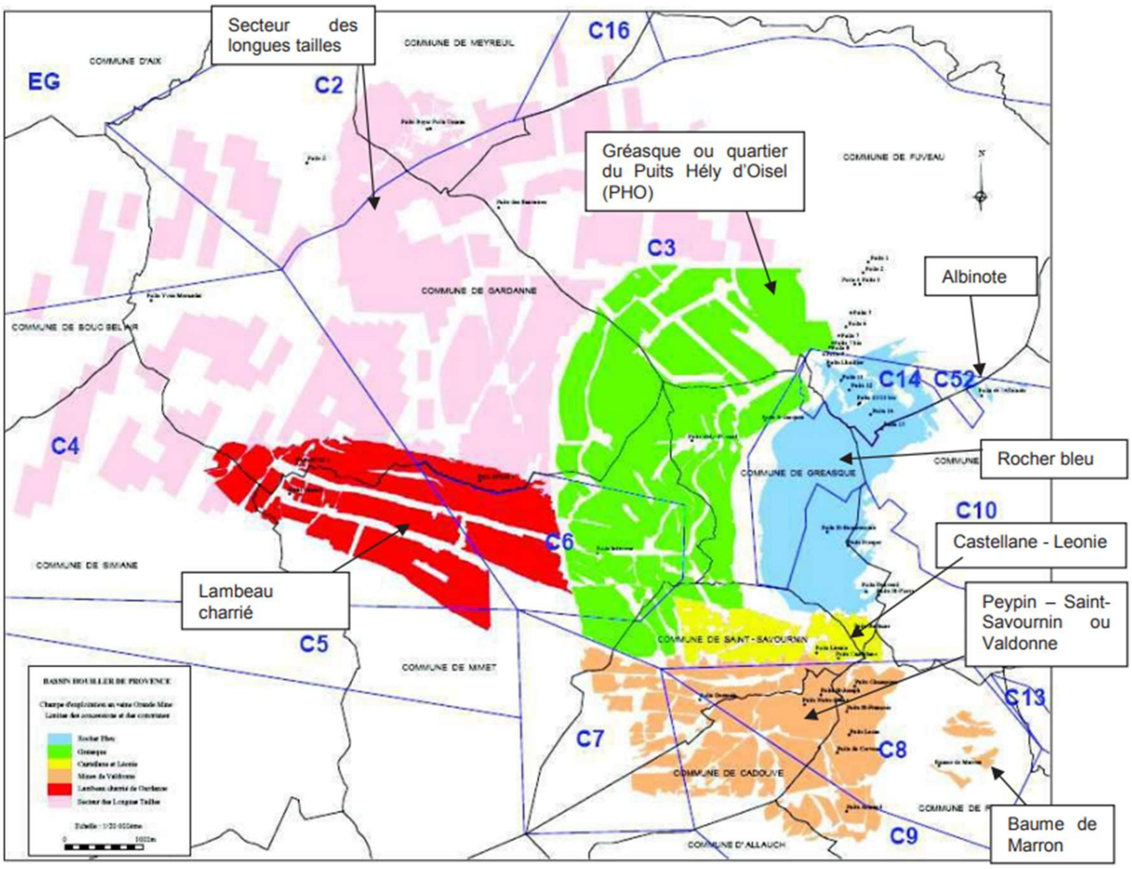

Figure 3: Lignite Basin of Provence – 16 concessions (C1-C16)

Source: http://www.bouches-du-rhone.gouv.fr/content/download/23759/143943/file/S2016-004DE_compress.compressed.pdf

The lignite (coal) seams depth increases from East to West. The Peypin sector is in the South-East part of the basin. The geology of the site is particularly disturbed due to the strong regional tectonic activity (Figure 3 and Figure 4). The sector is crossed by subvertical faults of general East-West orientation affecting the Cretaceous and Jurassic formations. Figure 4 presents the geology section of the coalmine and the underground quarry (mine).

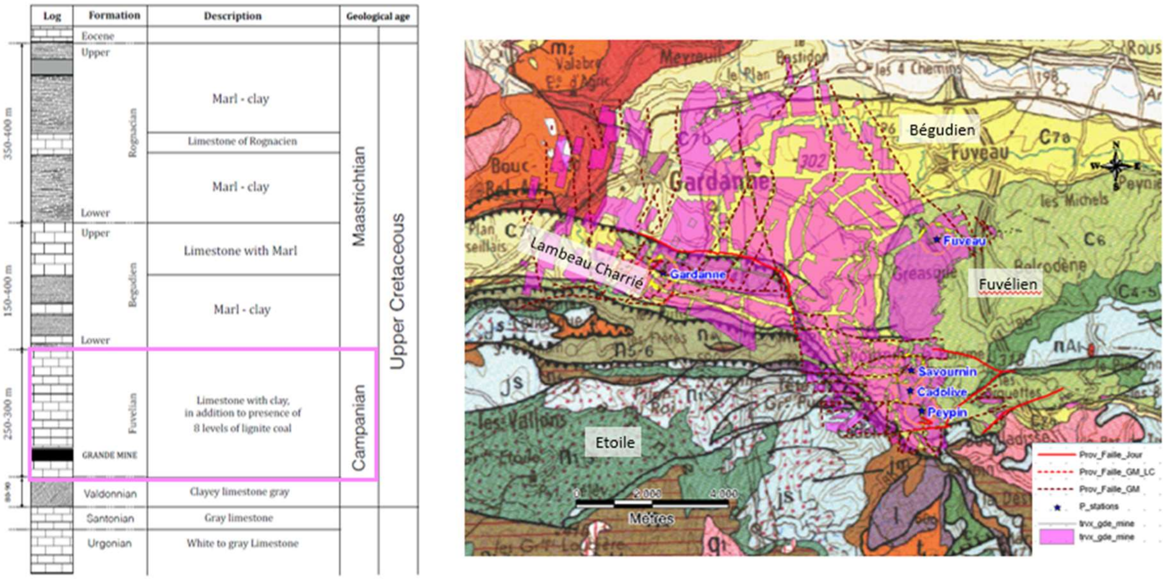

Figure 4: Geology of the Provence basin – the Peypin is in the south of the basin

The main characteristics of lignite mining in the commune of Peypin are as follows (Table 1):

- Gros-Rocher, operated at a power of 0.90 m, for an average opening (thickness operated) of 1.10 m.
- 4-pans, operated on a power of 1.00 m, for an opening of 1.20 m.
- Mauvaise-Mine, with a low power (< 0.60 m), very little undermined.
- Grande-Mine, the main layer of the beam, operated over an opening of 3.00 m (for an average power of 4.5 m) which ensured most of the production.

Table 1: Characterisation of the exploitation of the basin of Provence – Peypin town

Towns	Period	Depth	Extraction methods	Extraction ratio	Layers
Allauch, **Peypin**, Cadolive, Saint Savournin, Mimet	1860-1959	50 to 800 m	Irregular rooms and pillars	75 to 85 %	Gros Rocher 4 Pans and Mauvaise Mines
Saint Savournin – **Peypin** – Gréasque	1845-1920	120-500 m	Irregular rooms and pillars		Gros Rocher 4 Pans
La Bouilladisse - **Peypin**	1743-1911	0-140 m	Irregular rooms and pillars, small backfilling long-wall panels.		Mine de Gréasque, 2 Pans, Gros Rocher, and 4 Pans ; Mauvaise Mine.

Additionally, cement stone layer has been intensively mined in this sector mainly in two layers. The first layer, "La Valentine", is 1.70 m thick and is about 2.50 m from the second layer, "Portland", which is 2.50 m thick. The town of Peypin is affected by underground quarries and natural cavities. The underground quarry (mine) corresponds to four distinct parts. The network is marked by a low dip, approximately five degrees. The galleries are mostly low (2 meters to 3 meters sometimes), all on one level. Today, these farms are abandoned. Most of these operations probably started in the open, before continuing in the form of extensive underground excavations. In the absence of reinforcement work, underground quarries undergo natural aging which inevitably leads to the ruin of the structures.

In the Peypin sector, 7 shafts were identified. The depth varies between 65 m to 349 m. In the municipality of Peypin, the slag heaps with a volume of between 1,500 m3 and 30,000 m3 are stabilized and planted. During the mining operations, the mine was kept out of water by pumping for deep workings and by gravity flow galleries for small, isolated areas or upstream dips.

Identified hazards – Peypin town

Several hazards being identified in the municipality of Peypin by GEODERIS and the DREAL (French mining expert and mining authorities in France), we completed the information based on the collecting from existing documents. They can be grouped as follows:

- Natural hazards: forest fire; flood; natural seismicity; landslides; subsidence and collapse related to underground cavities, landslide - falling rocks and blocks.
- Mining hazards: ground movements (subsidence and landslide), flooding, heating.
- Technological" hazards related to soil pollution,

Due to the coalmine (lignite) extraction and the existing of dumps (Figure 3), 6 residual mining hazards were identified: ground movement (subsidence, sinkhole, settlement, landslide) and combustion, and induced seismicity. The level of each single hazard was assessed based on the specific characterisations of the hazard and the site. Figure 6 represents the mining hazards identified at Peypin town. We noticed the existing of several mining hazards in the identical zone. However, the interaction between the hazards has not been studied before. It is the objective of POMHAZ project.

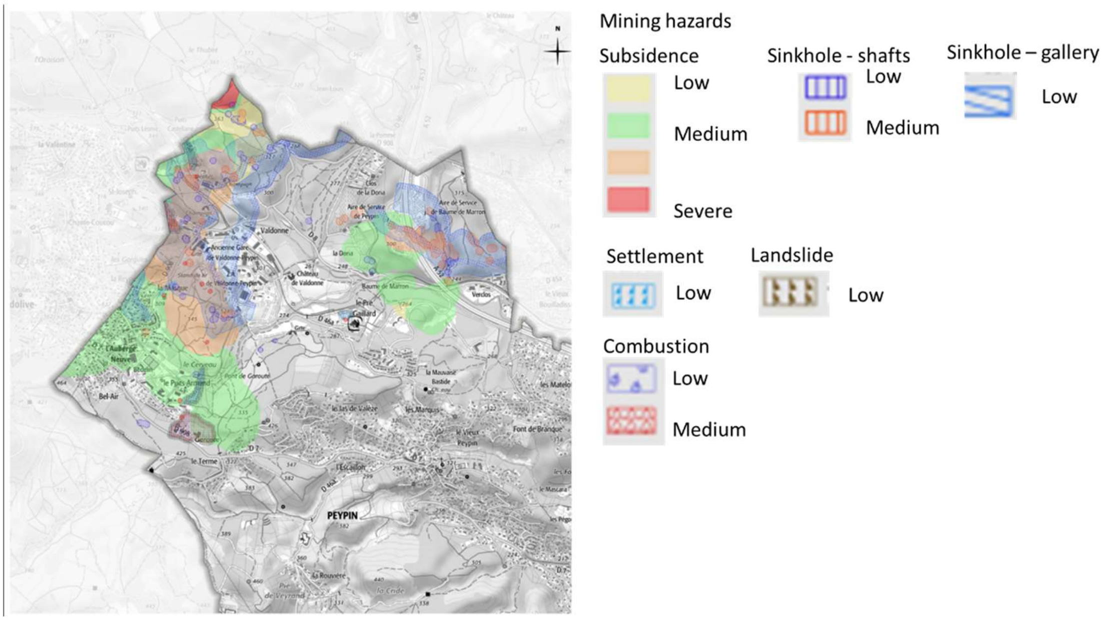

Figure 5: Mining hazards identified in Peypin town. This hazard map is not considered the induced seismicity

Source: https://www.bouches-du-rhone.gouv.fr/Actions-de-l-Etat/Environnement-risques-naturels-et-technologiques/La-prevention/Les-plans-de-prevention-des-risques-naturels-approuves-dans-les-Bouches-du-Rhone/PEYPIN

Five natural hazards have been identified in the municipality of Peypin: forest fire; flooding, natural seismicity, ground movements (subsidence and collapse linked to underground cavities, landslide - falling rocks and blocks and landslide) and shrinkage-swelling of clays. The underground cavities (quarry and natural cavities) present a ground movement hazard (sinkhole and subsidence). The analysis carried out by the local authorities identified two zones with two level of ground movement hazards: low and medium

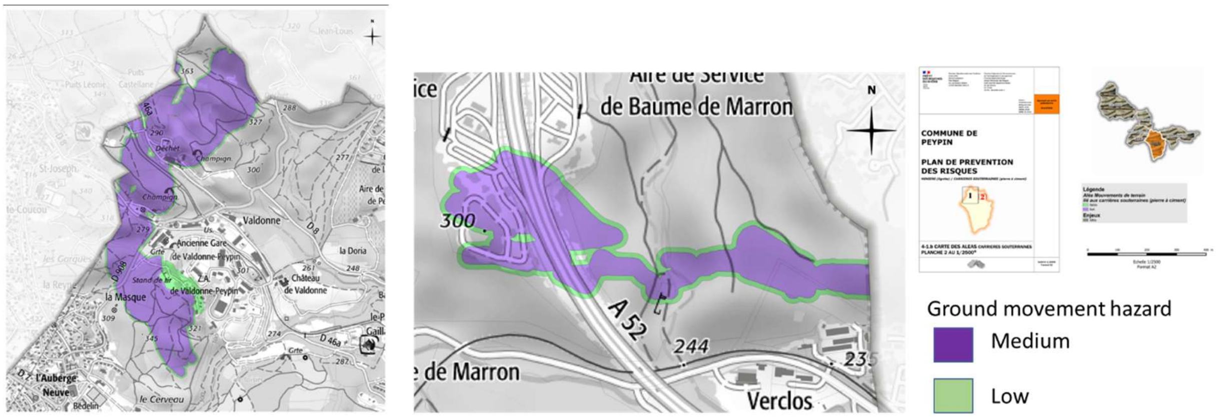

Figure 6: Ground movement hazard localisation – limestone quarry (mine) - Peypin town

Source : https://www.bouches-du-rhone.gouv.fr/Actions-de-l-Etat/Environnement-risques-naturels-et-technologiques/La-prevention/Les-plans-de-prevention-des-risques-naturels-approuves-dans-les-Bouches-du-Rhone/PEYPIN

Table 2 presents the level of each single hazards, mining and natural hazards. One can notice that the natural hazards are severe hazards relatively to mining hazards.

Table 2: Coal mine -intensity level (low=orange, moderate=purple, severe and very severe=red) of the mining hazards (6) and natural hazards (5).

Hazard		Low	Medium	Severe
Mine hazards (6)	Sinkhole (SIN)			
	Subsidence (SUB)			
	Landslide (LSG)			
	Settlement (SET)			
	Combustion (COM)			
	Induced seismicity (INS)			
Natural hazards (5)	Sinkhole (SIN)			
	Clay shrinkage – swelling (SET)			
	Natural seismicity (NSI)			
	Flooding (FLO)			
	Wildfire (FFI)			

The technology hazards identified in the Peypin town are related to the industrial activities: gas explosion, reject of chemical product, and fire of some industrial products. The level of the technology hazards is not existing.

2.3. Megalopolis lignite mine case study-Greece

The Megalopolis lignite mine is located in the central part of the Peloponnese region in Greece (Figure 7). The basin lies in a broad intermontane plain surrounded by mountain ranges such as Taygetos and Mainalo. It is situated near the city of Megalopolis, approximately 30 km west of Tripoli and about 200 km southwest of Athens. Large-scale surface lignite mining has taken place in the area since the 1970s to supply the Megalopolis power plants. Today, the mines are in the closure phase.

Figure 7: The location of the case study in Greece

2.3.1. Geological information

The Megalopolis lignite basin in central Peloponnese is characterized by a complex stratigraphic sequence that has strongly influenced both the development of lignite mining and the post-mining evolution of the area. The overburden consists mainly of Neogene and Quaternary sediments, dominated by marls, clays, and locally sandy deposits, which usually act as low-permeability layers. Their thickness varies considerably, ranging from only a few meters to several tens of meters, while in some areas they are absent, allowing older geological formations to crop out. Beneath the overburden, the basin is underlain by extensive karstified limestones, which form the dominant aquifer system in the region. These limestones are highly fractured, cavernous, and hydraulically active, with permeability enhanced by both tectonic discontinuities and dissolution features. The lignite seams are of Plio–Pleistocene age and occur at shallow depths, enabling extensive surface exploitation since the 1970s.

The Megalopolis basin is characterized by a relatively flat morphology, enclosed by the surrounding mountain ranges of Mainalo, Lykaion, and Taygetos. The basin itself covers an area of about 180 km^2 at an average elevation of approximately 410 m above sea level, while the absolute relief varies between ~350 m and ~500 m. The terrain is composed of broad flatlands intersected by low rounded hills and a dense drainage network. Slopes within the basin are generally gentle, ranging between 0 and 25%, while small canyons with depths of around 10 m are formed at the basin margins

The Megalopolis lignite basin is situated in a tectonically active region of the central Peloponnese. The western Peloponnese, including the Megalopolis area, is considered to lie within a zone of moderate to high seismic hazard. Recent seismic hazard zonation places the Peloponnese region among zones that correspond to stronger ground shaking potential.

2.3.2. Mining methods

The Megalopolis lignite basin has been exploited exclusively through surface mining, without the development of underground shafts or adits, due to the shallow depth and extent of the deposits. Since the early 1970s, when the Public Power Corporation of Greece (PPC) initiated a large-scale lignite exploitation, four major open pits have been developed: Thoknia, Choremi, Marathousa, and Kyparissia (Figure 8). The Thoknia mine was the first to be opened and remained active until 1994, when reserves were depleted. The Choremi and Marathousa pits have operated for several decades and continue to supply lignite to the Megalopolis power plants. The Kyparissia mine, however, faced serious hydrogeological challenges due to intense groundwater inflows from karstic aquifers, which ultimately forced the cessation of operations in that sector. At the peak of exploitation, the active mining areas covered approximately 20 km^2, while waste deposits occupied an additional 8.5 km^2. Following Greece's commitment to decarbonization and the gradual phase-out of lignite, exploitation in the Megalopolis basin has been reduced significantly. Current estimates suggest that active mining will continue at a diminishing scale until around 2028-2030, while complete cessation of operations is projected for 2040. After this time, the focus will shift entirely to post-mining land reclamation, environmental restoration, and alternative land uses, including renewable energy development.

In total, therefore, four large surface lignite pits have defined the mining activity in the Megalopolis basin. No vertical shafts or underground galleries have been constructed, and the mining operations are entirely characterized by open-pit techniques and associated waste dump formations.

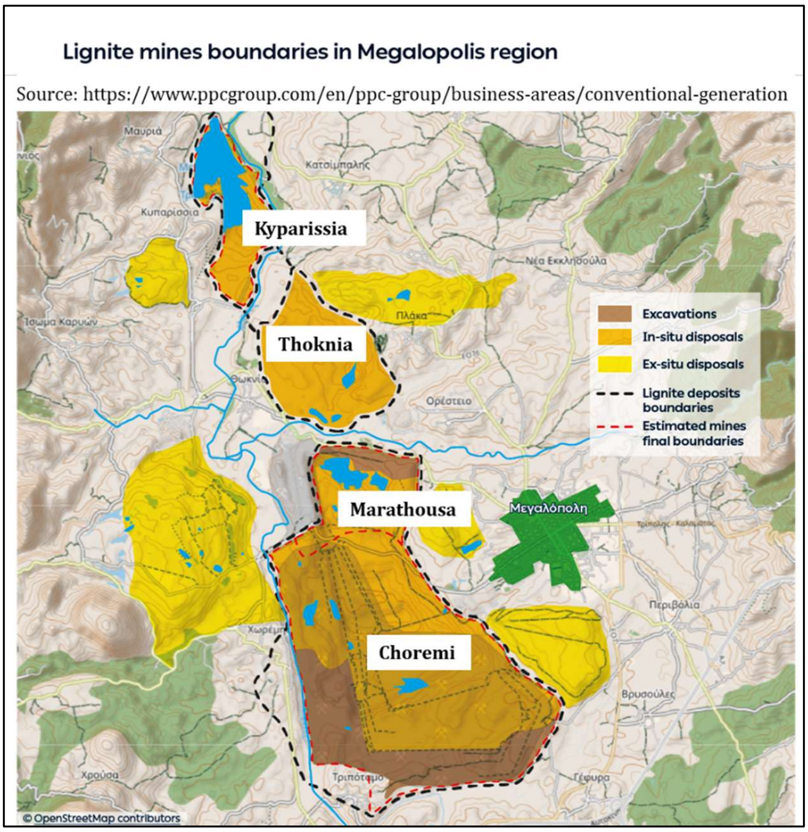

Figure 8: Megalopolis lignite mines' boundaries

2.3.3. Identification of hazards

In the Megalopolis post-mining area, slope movements represent the predominant post-mining hazard and have been selected as the focus of analysis. The hazard arises primarily from the geological and geotechnical conditions of the lignite-bearing formations, in combination with the extensive surface mining operations carried out by the Public Power Corporation (PPC). Excavations in Megalopolis, frequently encounter stability challenges due to the relatively low shear strength of the marls and clays that overlie and interbed the lignite seams.

Similarly to other mining areas, several hazards have been identified in the Megalopolis area, both natural and of mining origin.

In the Megalopolis post-mining area, slope movements represent the predominant post-mining hazard and have been selected as the focus of analysis. The hazard arises primarily from the geological and geotechnical conditions of the lignite-bearing formations, in combination with the extensive surface mining operations carried out by the Public Power Corporation (PPC).

The following natural hazards have been identified:

- Earthquakes –moderate to high seismic activity, high seismicity associated with the Hellenic arc system,
- Flooding to the presence of the Alfeios River and its tributary,
- Rainfall is a critical natural hazard in Megalopolis, acting both independently and as a trigger for slope instability and flood.

2.3.4. Hazards interaction

An interaction matrix of natural and mining hazards for the case study of Megalopolis post-mining area is presented (Figure 9).

			Secondary hazards			
			Mining	Natural	Natural	Natural
			Landslide	Earthquake	Flood	Rainfall
Primary hazards	Mining	Landslide				
	Natural	Earthquake				
	Natural	Flood				
	Natural	Rainfall				

Figure 9: Interaction matrix for the Megalopolis area incorporating post-mining and natural hazards

2.4. The southern Ruhr area-Germany

The Ruhr Area (Ruhrgebiet) in North Rhine-Westphalia, Germany, is a prime example of post-mining transformation in Europe. The metropolitan region under review here was once the industrial heartland of Germany, with a dominant presence of nearly 800 years of coal mining and over 170 years of steel production and heavy industries. The final active coal mine, Prosper-Haniel, ceased operations in 2018, signifying the conclusion of an era that has profoundly influenced the region's topography, economy, and societal structure.

The Ruhr Area, which covers approximately 4,400 square kilometres (Figure 10) and is home to over 5 million inhabitants, has undergone a remarkable structural change since the 1960s.

The case study lies in the transitional zone between the Westphalian Lowland (“Westfälische Bucht”) in the north and the Süder Uplands (“Süderbergland”) in the south. It comprises several characteristic natural regional units: the Emscher lowlands (“Emscherland”) in the northern section, the Hellweg Börden (“Hellwegbörden”) as the central landscape unit, and the Ardey Hills (“Ardeygebirge”) and Haarstrang as the southern boundary. The area is bisected from east to west by the Ruhr River. North of the river, the landscape is dominated by urban areas, while the south is more agricultural and forested.

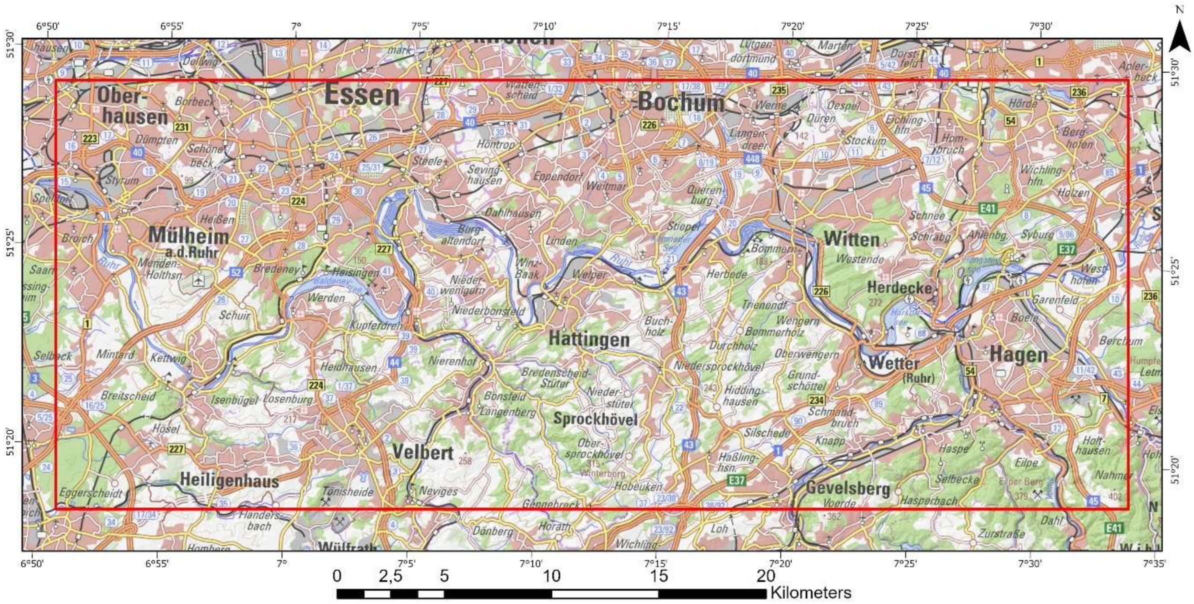

Figure 10: Combination of the digital topographic map 1:250,000 (DTK250) and a relief shading in the case study area.

The southern Ruhr Area is a particularly relevant case study for post-mining hazard assessment and management within the POMHAZ project framework. The selected, 1,000 square kilometres region (Figure 11) comprises cities such as Bochum, Essen, Dortmund and the surrounding municipalities, collectively representing a diverse landscape of former mining sites with varying geological conditions and urban development pressures.

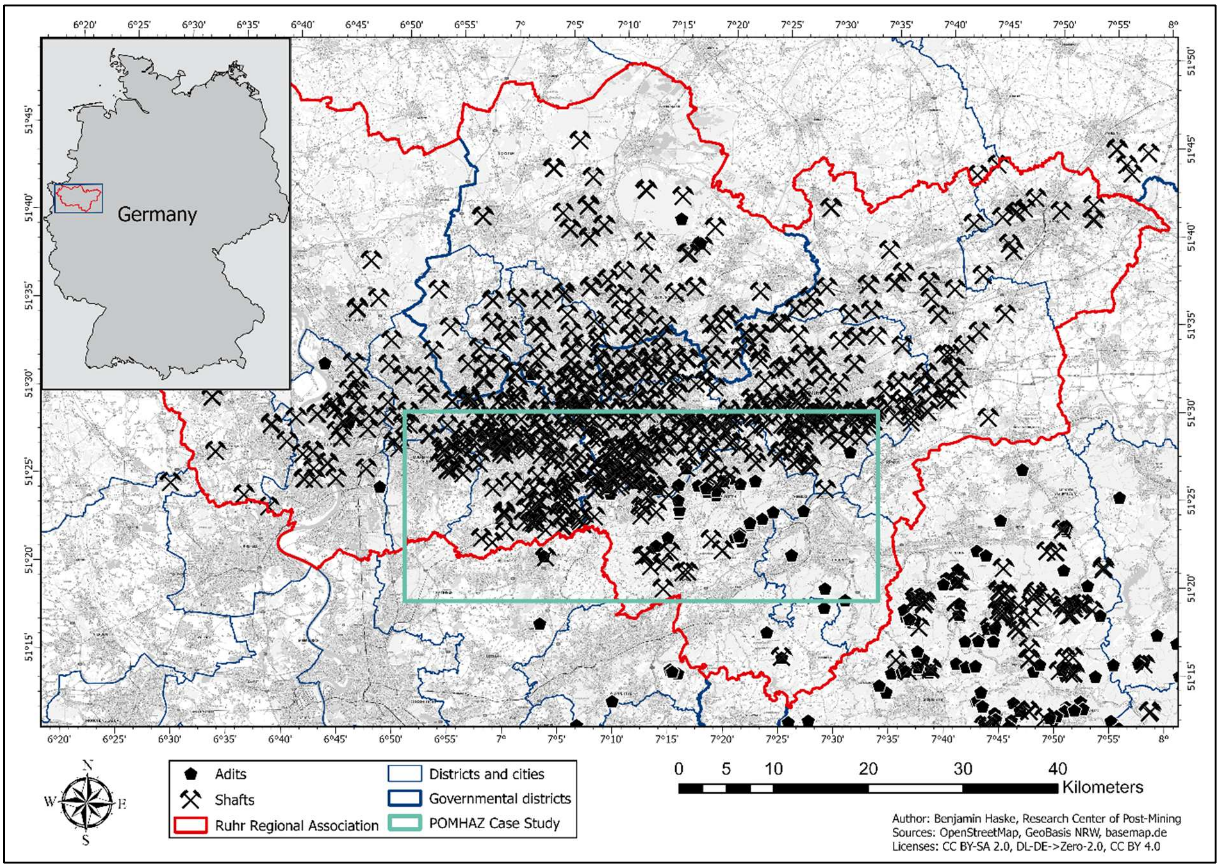

Figure 11: The Ruhr Area (red) in western Germany.

The green rectangle shows the sub-region investigated in the POMHAZ project in the southern area, which is mainly characterized by old, near-surface mining and dewatering adits.

2.4.1 Geological information

The geological foundation of the area is part of the Rhenish Massif and the Münsterland Basin, representing a complex structural framework that has been significantly influenced by Variscan tectonics and subsequent sedimentary deposition. The region's geological characteristics have been fundamental to its development as one of Europe's most important coal mining areas.

The bedrock underlying the southern Ruhr Area consists of Palaeozoic formations, primarily Upper Carboniferous rocks, which are unconformably overlain by younger Mesozoic and Cenozoic deposits (Figure 12). The structural geology reflects the complex tectonic history of the region, with numerous fault systems and folding events that have controlled both the original coal formation and subsequent mining operations.

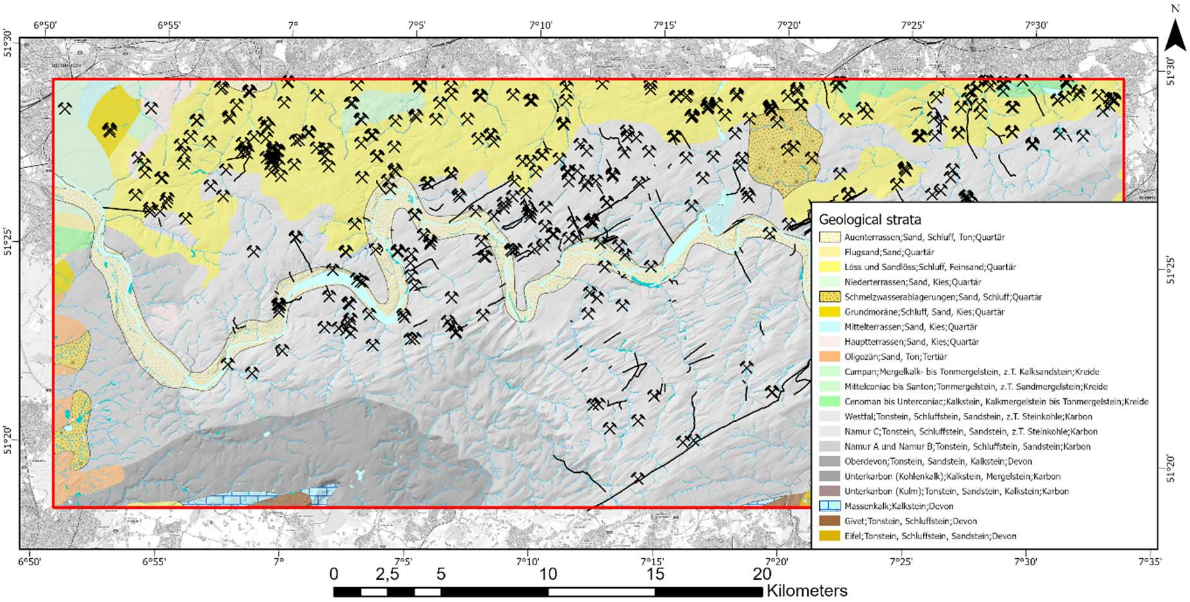

Figure 12: Geological overview of the study area.

The coal deposit dips toward the northwest, resulting in deeper mines and shafts concentrated north of the Ruhr River (center). Along and south of the river, Carboniferous strata (light grey) are exposed at the surface, where shallow mining operations and dewatering adits are primarily situated.

The most important geological formations are as follows:

- Quaternary deposits, often heavily modified by anthropogenic activities related to mining operations, urban development, and industrial processes,
- Upper Carboniferous (Pennsylvanian): represent the most economically important geological unit in the southern Ruhr Area. These sediments belong to the Namurian and Westphalian series and are composed of a cyclic sequence of sandstones, siltstones, mudstones, shales, and conglomerates, within which numerous coal seams are intercalated. The coal seams within these formations are characterized by their considerable thickness (locally exceeding 3 meters), good quality with high calorific values, and relatively low methane content compared to deeper mining areas. The shallow occurrence of these coal-bearing formations, with numerous surface outcrops, was particularly favorable for the early development of mining operations in the region,
- Devonian formations are represented by Middle and Upper Devonian limestone and dolomite sequences. These carbonate rocks, reaching thicknesses of up to 200 meters, contain important karst aquifer systems.

2.4.2. Characterisation of the exploitation of the area of southern Ruhr Area.

The Ruhr region has witnessed the implementation of a variety of coal mining methods throughout the centuries. The technology utilised in this field encompasses a wide spectrum, ranging from basic surface mining techniques to the employment of adits and deep shafts, incorporating industrial technologies. As the deposits were explored, mining operations became progressively deeper. As the deposits were further explored, mining activities transitioned to deeper levels in the northern direction.

The earliest and most basic methods of mining entailed the straightforward excavation of the surface until the groundwater level was attained. From the 16th century onwards, trenches were excavated in the valleys, with the seams being led higher up the valley slope, with the trenches being as deep and wide as the thickness of the seams permitted. Subsequently, these tunnels were extended horizontally into the mountain, thus enabling the continuation of mining operations below the surface. The tunnel's gradient towards its mouth facilitated effective drainage. From the 17th century onwards, so-called dewatering adits, or "Erbstollen" in German, also became established. The early drainage tunnels represented a significant technical advancement. The implementation of natural slopes in mining operations has led to the elimination of the requirement for mechanical pumping systems. This development has enabled the effective drainage of entire mining areas, thus facilitating the process of extraction.

The dewatering adits were utilised not only for the drainage of water, but also for the ventilation (air supply) and the transportation of personnel and materials. The introduction of steam engines around 1850 marked the decline of adits, as mine water could now be extracted mechanically. However, many of these centuries old systems are still in operation today, passively dewatering big areas in the southern Ruhr area. The utilisation of steam engines also enabled the mining of deeper seams by constructing deeper shafts.

The room-and-pillar method (German: "Örterbau") was utilised in particular, both with and without backfilling, and adits and shafts were employed. The absence of comprehensive documentation, or the presence of incomplete documentation, pertaining to these near-surface mining operations and their development status, poses a significant hazard.

As industrialisation of mining intensified towards the close of the 19th century, deeper seams were mined in response to the depletion of near-surface deposits. The mining industry underwent a significant geographical shift, moving further northwards. The seams in question were found to be predominantly horizontal, thus rendering the longwall mining method – which has been proven to be significantly more efficient – the optimal choice for extraction. This method initially involved the use of mining hammers, and subsequently incorporated coal plows and shearers. This method induced the collapse of the rock directly behind the mining front, resulting in rapid and substantial subsidence. However, no long-term hazards were indicated, as opposed to the unsafe room-and-pillar mining.

Due to centuries of mining, the exact number of mines, shafts and adits in the study area is unknown. Some areas were subject to small scale surface mining (e.g. coal pits and pingen), but there were no large open-pit mines. As part of the evaluation of documents available to the North Rhine-Westphalian Mining Authority, approximately 31,000 abandoned mine openings (including tunnels and shafts) have been identified in the state to date. The number of undocumented cases is significantly higher.

Coal mining started in the area possibly as early as the 12th century, the first documented references date back to 1296 and 1302. Mining in this area reached its peak during the Industrial Revolution of the mid-19th century, continuing until the early 20th century. Once the reserves had been exhausted, coal production moved further north in search of deeper deposits. After World War II, many small mines were briefly reopened due to severe hardship in order to extract the remaining coal from these deposits. This extraction was often illegal, but tolerated due to the dire circumstances. The near-surface mining was not documented, meaning it still poses significant hazards to the surface today.

2.4.3. Identified hazards

Several hazards have been identified in the southern Ruhr Area, both natural and of mining origin.

The following natural hazards have been identified:
- Earthquake,
- Shallow landslide,
- Rockfall,
- Flooding by runoff and mudslides,
- Rainfall.

The intensity and frequency of these hazards vary, depending on the different factors.

Mining hazards have been identified, among which:
- ground subsidence is one of the most prevalent and persistent post-mining hazards in the southern Ruhr area. In the southern Ruhr area, subsidence processes are influenced by the depth of historical mining activities (ranging from shallow workings at depths of 30–50 metres to deep mining operations exceeding 1,000 metres), the thickness of extracted coal seams, the extent of backfilling during mine closure and the geological structure of the overburden. In the southern Ruhr area, the depth of the subsidence typically ranges from 0.5 to 8 metres,
- sinkholes. The mining authority counted 241 mining-related sinkhole events in the area from 2006 to 2022,
- gas emission linked to mining: the release of methane, carbon dioxide and other gases from abandoned underground workings. In the southern Ruhr area, gas emission patterns are influenced by mine flooding and the subsequent rebound of groundwater,
- hydrological disturbances, the complex phenomena involving changes to surface water and groundwater systems. The main result is the creation of permanent bodies of water (polders) in subsidence basins, which fundamentally alters local drainage patterns and flood risk characteristics.
- environmental pollution from spoils: contamination pathways include leachate generation from waste piles affecting groundwater quality, dust emissions from exposed waste surfaces and the mobilisation of heavy metals and other contaminants during precipitation events,
- combustion and overheating of mine waste, influenced by various factors, including the coal content and particle size distribution of the waste materials, the availability of oxygen through porosity and permeability, the moisture content, and the ambient temperature conditions.

3. Summary

Within Work Package 5 (WP5) of the POMHAZ project, the main goal was to validate the GIS and DSS tools developed for multi-hazard assessment and management in post-mining areas under real conditions. The work focused on four case studies (Poland, France, Germany, and Greece), with the Polish partner GIG-PIB responsible for three representative cities: Wałbrzych, Sosnowiec, and Piekary Śląskie. Each city represented a different stage of mine closure and post-mining transformation, allowing a comparative evaluation of hazard types, data availability, and the adaptability of the tools to local needs.

The activities included collecting and analysing geological, mining, hydrological, and environmental data to prepare input for the GIS/DSS systems and to verify user requirements. The key objectives were to integrate local data, identify and rank post-mining hazards, and test the performance of the tools with end users such as municipalities and coal companies (e.g. SRK S.A.). Thirteen potential hazards were initially analysed, including subsidence, sinkholes, flooding, and gas emissions (methane, radon, CO_2).

In Wałbrzych, where mines were closed over 20 years ago, field studies measured gas concentrations and surface movements, confirming that gas emissions are minor but that hydrological disturbances remain a significant problem. Sosnowiec and Piekary Śląskie, where mine flooding is ongoing, required dynamic analyses linking surface deformation with groundwater level changes. Long-term radon measurements in public buildings and schools confirmed the tool's predictions of elevated concentrations, especially in shallow mining zones.

The results demonstrated a strong correlation between GIS/DSS risk maps and real observed damage, particularly for subsidence and flood hazards. Verification with city representatives led to an updated ranking of hazards and refined datasets for further tool calibration. The analysis also showed that the degree of risk depends strongly on local geological conditions, the stage of mine closure, and the availability of reliable data.

A classification of post-mining areas was developed to determine their suitability for construction and redevelopment, based on the degree of ground deformation and hazard occurrence (categories A–C). This framework supports local authorities in spatial planning and in preventing construction in high-risk areas such as floodplains, shallow mining zones, or active sinkhole regions.

Overall, WP5 confirmed that the POMHAZ GIS/DSS tools are effective instruments for multi-hazard risk assessment, providing a scientific basis for sustainable land-use decisions in post-mining regions. Their use enhances cooperation between scientists, municipalities, and industry, helping to mitigate long-term environmental and structural risks in former mining cities.

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What is PoMHaz?

The goal of PoMHaz is to improve methodological and practical knowledge for the assessment and management of multi-hazards, at the scale of a coal mining basin, through the active and continuous engagement of key stakeholders involved in or affected by post-mining activities.

PoMHaz is a project funded by the Research Fund for Coal and Steel programme.

Further information can be found under https://www.pomhaz-rfcs.eu.

For feedback on the PoMHaz project or the published deliverables, please contact contact@pomhaz-rfcs.eu.

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