Post-Mining Multi-Hazards evaluation for land-planning

PoMHaz

WP5: Application on real case studies

D18: Deliverable D5.3 - GIS and DSS implementation on real case studies

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Acronyms

AI	Artificial Intelligence
AOI	Area of Interest
CERTH	Centre for Research and Technology Hellas
DMT	DMT-Gruppe (Deutsche Montan Technologie)
DSS	Decision Support System
EAR	Elements at Risk / Exposed Elements at Risk
EU	European Union
FZN	Forschungszentrum Nachbergbau / Research Centre of Post-Mining
GDP	Gross Domestic Product
GDU	Geologischer Dienst / Geological Service
GIS	Geographic Information System
LU/LC	Land Use/Land Cover
MHI	Multi-Hazard Index
NRW	North Rhine-Westphalia (Nordrhein-Westfalen)
OSM	OpenStreetMap
POMHAZ	Post-Mining Multi-Hazards evaluation for land-planning
RFCS	Research Fund for Coal and Steel
sDSS	Spatial Decision Support System
THGA	Technische Hochschule Georg Agricola
VI	Vulnerability Index
WP	Work Package

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 5.3, is directly related to Task 5.2 “GIS and DSS implementation on real case studies”. This deliverable focuses on the outcomes of the application of GIS/DSS on case studies.

The GIS and DSS tools were carried out on southern Ruhr (Germany) area and Megalopolis lignite mine (Greece). The application tests in these post-mining areas have successfully demonstrated the operational capability and practical utility of the multi-hazard assessment methodology developed within the project framework. The data and the results of the analysis demonstrate the value of the DSS in the post coal region in transition. The validated interaction matrix methodology was used for both case studies. Different potential interaction scenarios are carried out and the results were analysed with the help of the stakeholders and mining authorities.

The sDSS is a significant technological advancement in post-mining risk management. It combines established scientific principles with modern GIS technology and AI-assisted analysis to generate customised risk communication materials for diverse stakeholder audiences. It also maintains scientific accuracy and addresses critical multi-jurisdictional coordination challenges.

These case studies show that sophisticated, multi-hazard assessment approaches can be successfully implemented in complex, real-world environments. They provide essential tools for managing ongoing post-mining challenges and support sustainable development objectives by enabling evidence-based decision-making that considers stakeholder priorities, expert knowledge and technical capabilities.

The validation of the multi-hazard and multi-risk methodology confirms that the sDSS can be used for operational deployment for real applications. However, additional effort should be taken for considering the policy and economic aspects to measure the cost-benefit of the multi-risk analysis on the coal region in transition.

1 Background

1.1 Description of the WP5

Deliverable D5.3, entitled "GIS and DSS implementation on real case studies", refers to WP5 application of project's developed tools and methods on existing post-mining areas.

The overall goal of WP5 is to validate the usability of the tools (DSS and GIS) developed in previous work packages for multi-hazard management in real case studies. This validation is carried out by applying the tools in four different sites located in Poland, France, Germany, and Greece. Each site presents specific requirements and characteristics, making it essential to ensure the flexibility and adaptability of the proposed tools. The main objectives of WP5 are:

- To check end-user requirements in terms of GIS and DSS.
- To prepare dedicated tools supporting decision-making in spatial planning, integrating requirements from partner towns and the SRK company with respect to long-term development, environmental conditions, infrastructure, and urban features.
- To design tailored GIS and DSS tools based on detailed data and requirements formulated by end users and administrators of the selected test sites.
- To provide the required data for testing the GIS and DSS.
- To integrate and verify end-user requirements into the developed tools.

The work package consists of three main tasks:

Task 5.1 End-user requirements and data collection

Task 5.2 GIS and DSS implementation on real case studies

Task 5.3 Discussion of the results – Workshop

1.2 Description of the T5.2

The GIS and the DSS have to be tested in case studies in Germany, Greece and, additionaly, France. DMT-THGA, CERTH and Ineris worked together to apply the methodology developed in WP3 and WP4. In particular, the GIS was applied to the case studies in the Southern Ruhr area (Germany), as well as in Megalopolis area (Greece) and Peypin (France). These sites are different, concerning not only geology but also the period since mining was stopped, therefore it would give valuable data for temporal risk development. Due to urban circumstances at chosen sites, there are specific demands for future development and decision making.

All problems detected during the specific application on the case studies have been fixed.

The DSS is able to identify the hazards based on indicators such as ground movements or water quantity changes so that the end-user can assess the situation appropriately and implement mitigation measures.

2 Geographical localisation of the case study (with national, regional map)

In this deliverable, two case study sites were selected for the implementation of the GIS and DSS tools: the Southern Ruhr area in Germany and Megalopolis post-mining area in Greece.

2.1 Southern Ruhr Area in Germany

The Ruhr Area (Ruhrgebiet) in North Rhine-Westphalia, Germany, is a prime example of post-mining transformation in Europe [1]. 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 [2]. The final active coal mine, Prosper-Haniel, ceased operations in 2018 [3, 4], signifying the conclusion of an era that has profoundly influenced the region's topography, economy, and societal structure (Figure 1).

The Ruhr Area, which covers approximately 4,400 square kilometres (Figure 2) and is home to over 5 million inhabitants [5], has undergone a remarkable structural change since the 1960s [6]. The region is currently grappling with the intricate challenge of overseeing the aftermath of extensive mining operations while concurrently embarking on a transition towards a sustainable, knowledge-based economy [7]. This transformation is predicated on the resolution of numerous environmental, social and economic issues that have arisen over the course of several decades of resource extraction. Figure 1 shows an example of the historical development of the workforce and coal production in Germany over the last 200 years, with a concentration in the Ruhr region.

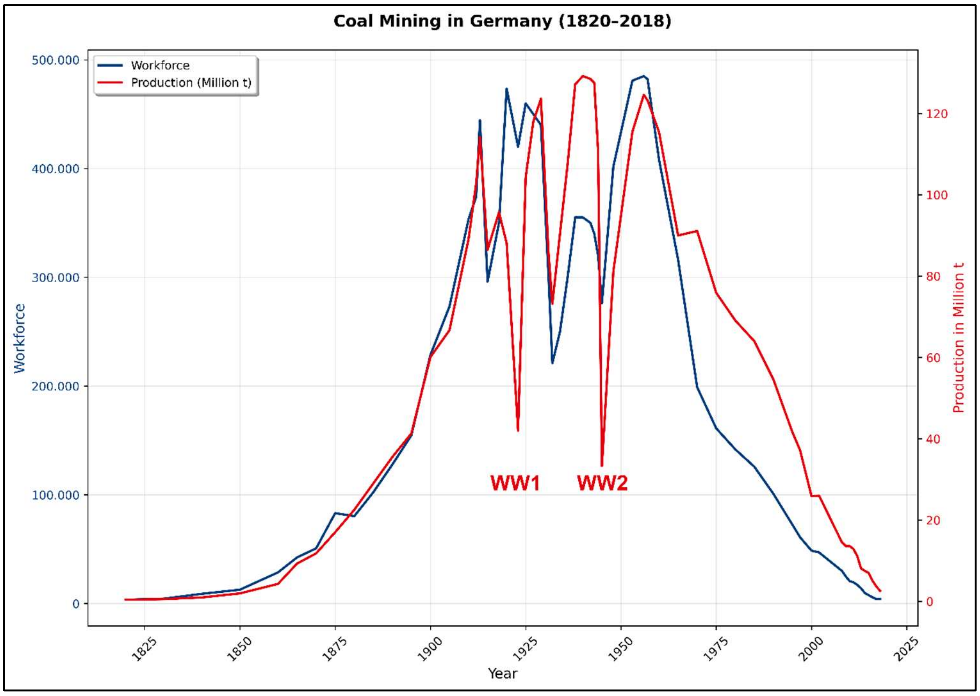

Figure 1: Chronological overview of the workforce and hard coal production in Germany from 1820 until the closure of the last mine in 2018. In addition to the general trends, there were also sharp but short-term declines in production during World War I and World War II. Statistical data: [8 – 12].

The post-mining landscape is characterised by subsidence areas, challenges to groundwater management, contaminated sites, and the need for comprehensive land use planning.

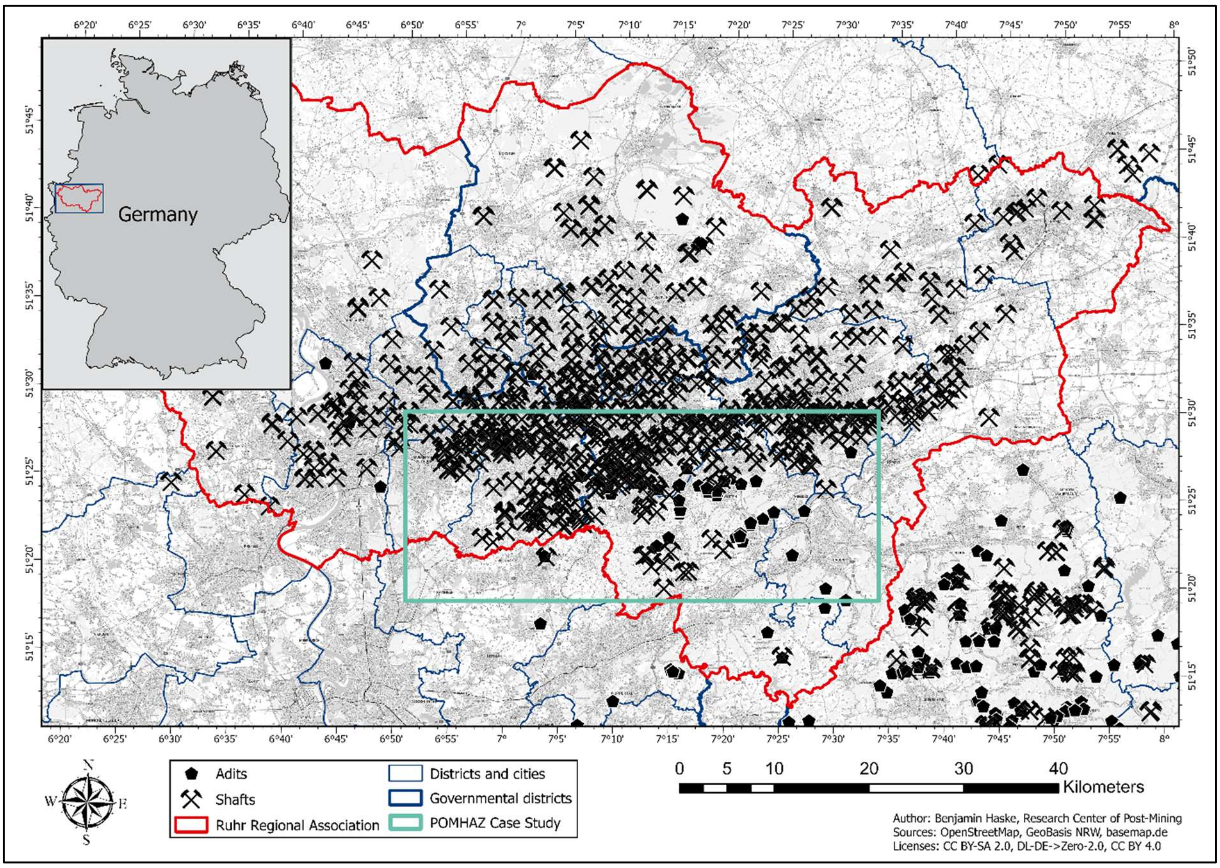

Figure 2: The Ruhr Area (red) in western Germany. The green rectangle shows the sub-region investigated in the POMHAZ project in the southern area, which is mainly characterized by old, near-surface mining and dewatering adits. Map data: [13 – 15].

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 2) 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.

The southern Ruhr Area is distinguished by its intricate geological setting, characterised by the presence of multiple aquifer systems that have been impacted by historical mining operations (Figure 3). The necessity of ongoing dewatering through the utilisation of adits with a history extending over centuries [2, 16], in conjunction with documented and undocumented near-surface mining practices [2], has given rise to persistent challenges concerning hazards such as sinkholes and hydrological disturbances. The region displays considerable variations in ground-movement patterns, with some areas experiencing ongoing subsidence [17] while others can see rapid sinkhole events [18]. The presence of mine gas and other post-mining and natural hazards must also be addressed, as they are also critical factors [19].

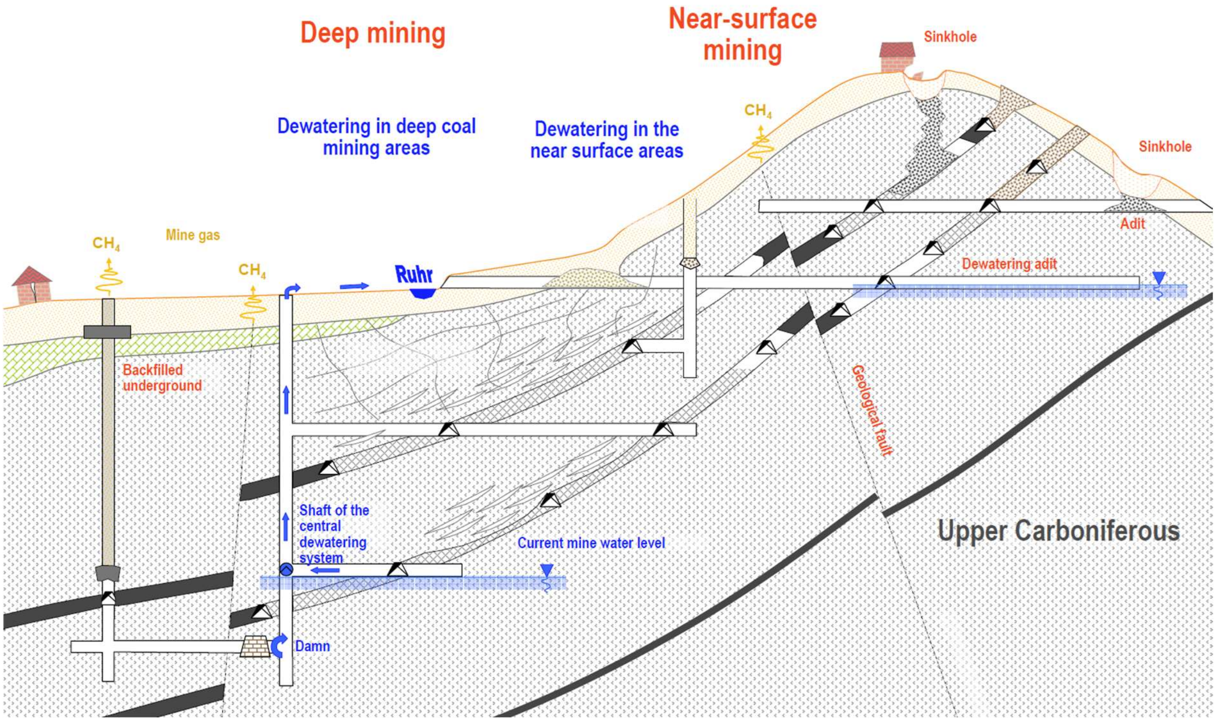

Figure 3: Schematic north-south cross-section of the coal deposit in the southern Ruhr area, showing mining operations and associated hazards. Modified from [20].

This area offers an ideal laboratory for studying post-mining hazards due to its documented mining history, extensive monitoring networks, and diverse range of surface uses. The presence of residential areas, commercial districts, transportation infrastructure, and recreational spaces above former mining areas provides a comprehensive setting for assessing risk scenarios and developing adaptive management strategies.

The southern Ruhr Area's experience with mine closure, environmental rehabilitation, and urban redevelopment renders it a valuable case study for understanding the long-term implications of post-mining transitions and the effectiveness of various hazard mitigation approaches in densely populated former mining regions [1, 4].

2.2 Megalopolis lignite mine in Greece

The Megalopolis lignite mine is located in the central part of the Peloponnese region in Greece (Figure 4). 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, leaving extensive post-mining landscapes that include open pits, internal dumps, and areas planned for reclamation and renewable energy projects (Figure 5).

Figure 4: The location of the case study in Greece

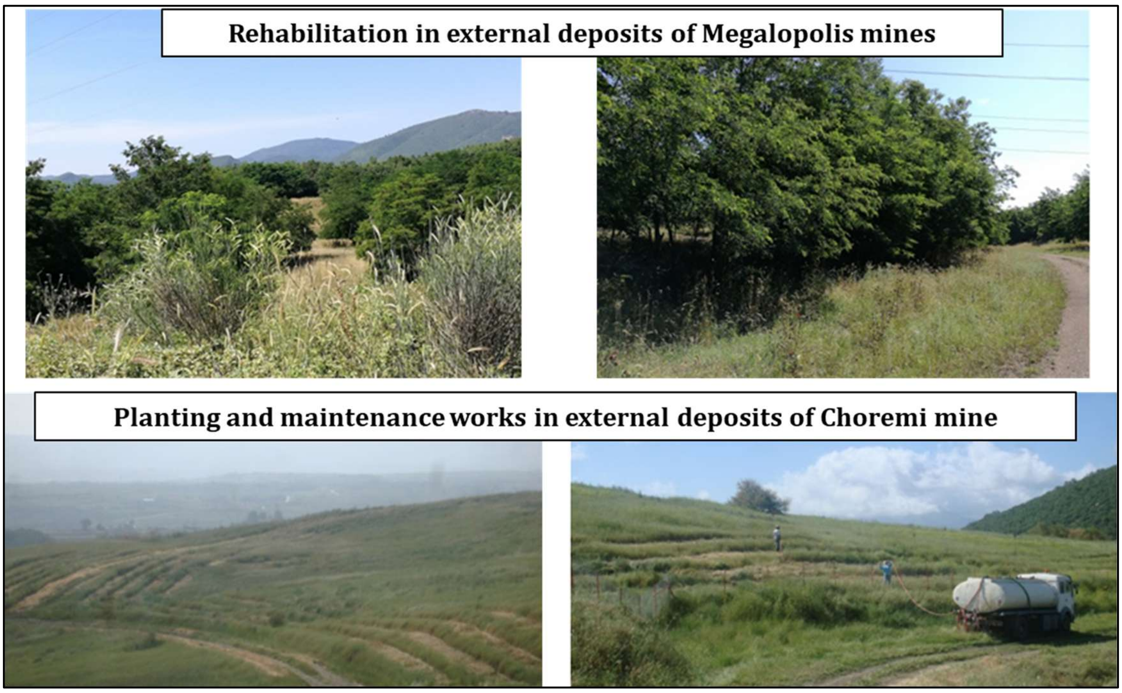

Figure 5: Rehabilitation works in post-mining area of Megalopolis [57]

3 Description of the coal mines including geology, mining method, etc.

3.1 Geology and Hydrology

3.1.1 Southern Ruhr Area in Germany

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 [21-22]. 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 **6**). 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 [21-22].

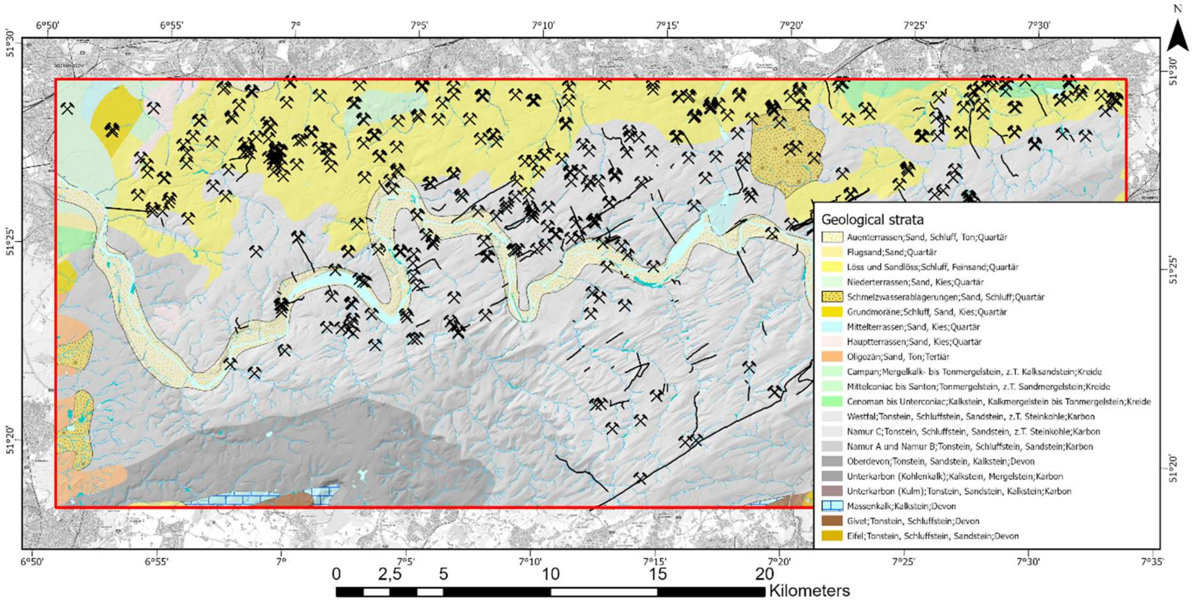

Figure 6: Geological overview of the study area. Map data: [15, 16, 23, 24].

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.

Lithology and Stratigraphy

<u>Overburden</u>

Quaternary deposits, often heavily modified by anthropogenic activities related to mining operations, urban development, and industrial processes. These materials include mining waste, slag heaps, backfill materials used for shaft closure, and various construction debris incorporated into the surface geology [25-26].

Quaternary

The Quaternary formations in the southern Ruhr Area have a variable thickness ranging from a few meters to over 40 meters, with the greatest accumulations occurring in river valleys and glacial channels. The lithological structure is highly heterogeneous both vertically and horizontally, reflecting the complex depositional history during multiple glacial and interglacial periods [22].

Sediments of this age were formed during the Saalian and Weichselian glaciations and the Holocene. The Pleistocene deposits are primarily represented by fluvioglacial sediments, including variously grained sands, gravels, and glacial till. These sediments were deposited on an erosional surface cut into the underlying bedrock and lie unconformably on Upper Carboniferous formations and locally on Devonian limestone [22].

The lower Pleistocene formations consist of poorly sorted medium- to coarse-grained sands, yellow-grey clays, and sandy loams. The clayey formations often contain residual weathering products and are locally mixed with weathered fragments of the underlying Carboniferous rocks and Createaceous rocks. In valley positions, impermeable clayey layers form important hydrogeological barriers.

Holocene sediments are primarily confined to river valleys, particularly along the Ruhr River and its tributaries. These deposits, several meters thick, are composed of variously grained alluvial sands, silts, and organic-rich river muds. Anthropogenic materials, including mining waste dumps and industrial slag, are also included within the Holocene formations [22].

Upper Carboniferous (Pennsylvanian)

The Upper Carboniferous formations 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 [22].

The Upper Carboniferous succession can be subdivided into several productive coal-bearing formations (Figure **7**), with different modern and historical names [21-22]:

- **Dorstener Schichten (Dorsten Beds)**: The youngest productive coal-bearing formation, corresponding to the Flammkohlenschichten (Flame Coal Beds). Contains coal seams with Germanic names including Baldur, Donar, Freya, and others. Composed of interbedded sandstones, siltstones, and coal seams with a thickness of 80-150 meters. This formation is largely removed by erosion in the study area.
- **Horster Schichten (Horst Beds)**: Equivalent to the Gasflammkohlenschichten (Gas Flame Coal Beds). Contains coal seams designated with letters including the Flöz Ägir seam shown in the diagram, as well as seams L, M, N, O, P, Q, R, S, T (Bismarck), U, V, W, X, and Y. Total thickness ranges from 150-250 meters.
- **Essener Schichten (Essen Beds)**: Corresponding to the Gaskohlenschichten (Gas Coal Beds). Contains the Flöz L seam (also present in Horster Schichten) and other lettered seams A through L, including the important Zollverein seams 1-9 and Viktoria seams. The total thickness ranges from 200-300 meters.

- **Bochumer Schichten (Bochum Beds)**: Equivalent to the Fettkohlenschichten (Fat Coal Beds). Contains the economically important Flöz Katharina seam along with numerous other seams including Sonnenschein, Dickebank, Präsident, and many others with personal names. Composed of alternating sandstones, siltstones, and coal seams with a total thickness of 180-250 meters.
- **Wittener Schichten (Witten Beds)**: Corresponding to the Esskohlenschichten (Forge Coal Beds). Contains the Flöz Plaßhofsbank seam (shown as Plathofbank in the diagram) along with other seams including Girondelle 1-9, Kreftenscheer 1-3, and Geitling 1-3. This formation has a thickness of 340-660 meters in the Ruhr area.
- **Sprockhöveler Schichten (Sprockhövel Beds)**: Equivalent to the Magerkohlenschichten (Lean Coal Beds). The oldest productive coal-bearing formation containing the Flöz Sarnsbank seam along with other seams including Sengsbänksgen (the oldest known coal seam in Ruhr mining), Sengsbank, Hauptflöz, and Schieferbank. This formation represents the transition from the underlying Namurian basement and has a thickness of 100-180 meters.

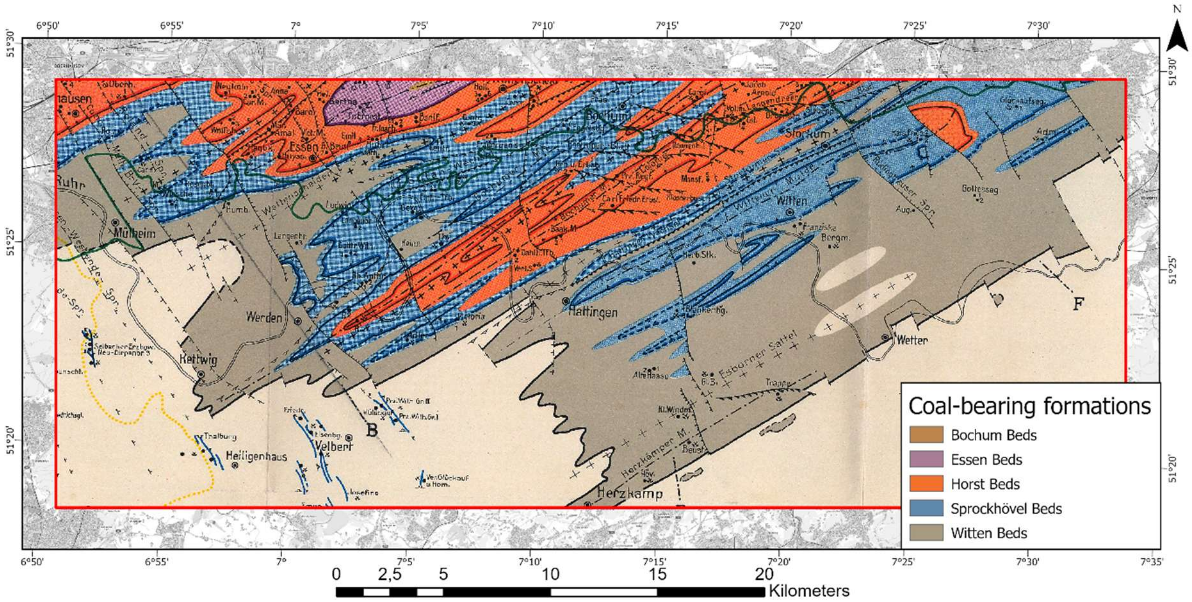

Figure 7: Coal bearing formations in the study case area. Map data: [13, 21].

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

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. The Devonian limestones are overlain by argillaceous formations and locally contain anhydrite intrusions and laminae [22].

Tectonics

The southern Ruhr Area is located within the Ruhr District structural zone, which forms part of the larger Rhenish Massif. The regional tectonics are characterized by a complex system of faults, folds, and block structures that developed during multiple deformation phases, primarily during the Variscan orogeny and subsequent Alpine reactivation [22]. Local structural complications, including anticlinal and synclinal structures, create significant variations in stratigraphic relationships across the region (Figure 8).

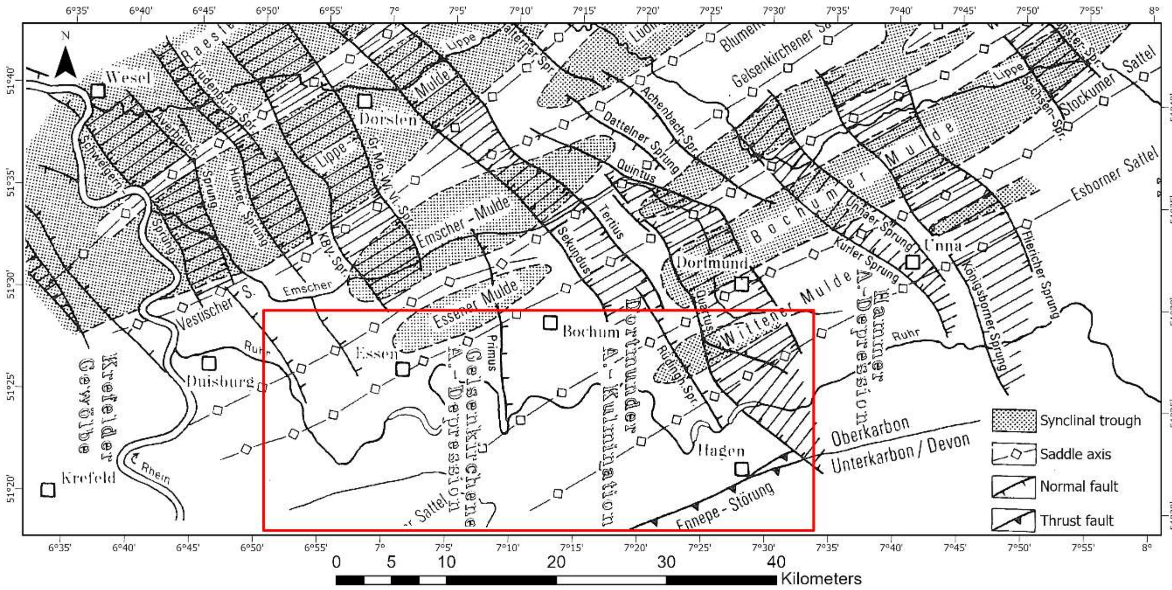

Figure 8: Tectonical overview of the Ruhr area, modified from [22].

The larger coal deposits in the north are located in synclinal troughs that could only be accessed via deep shafts in the industrial mining area. In contrast, mining in the case study area (shown in red) was shallow in an earlier period.

The regional dip of the coal-bearing strata is generally toward the north and northeast, with inclinations ranging from 5-15 degrees in the southern parts to nearly horizontal in the northern areas (Figure 9).

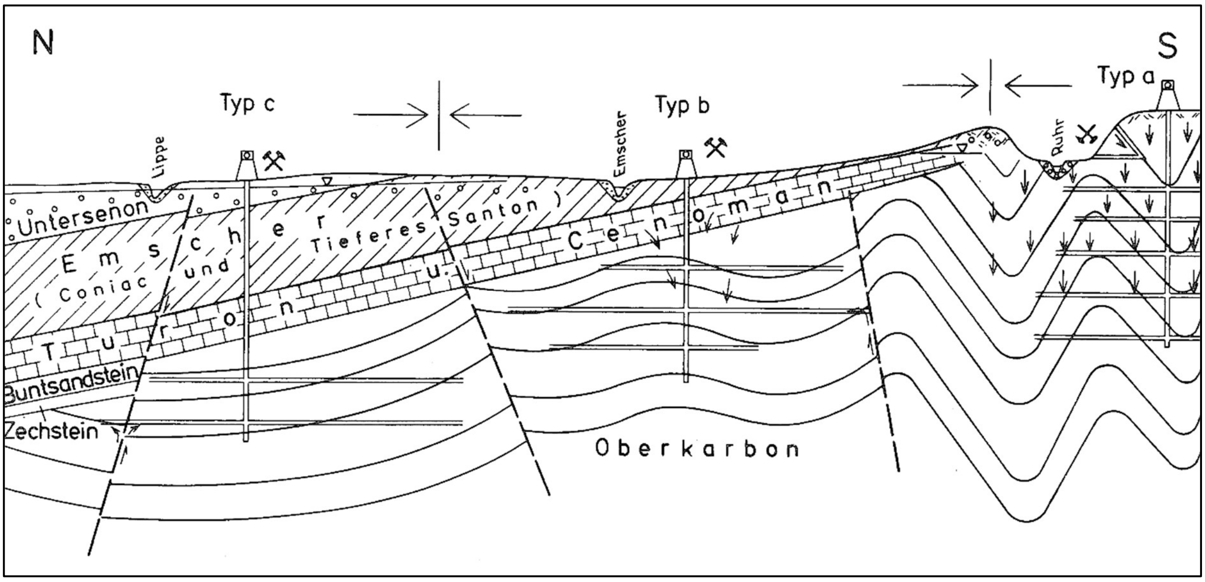

Figure 9: The regional dip of the coal-bearing ("Oberkarbon") and overlying strata [22].

The study area is located in the type a and b areas with little or no overburden.

The case study area is dominated by a system of predominantly NW-SE trending faults, often with significant vertical displacements reaching several hundred meters. These fault systems have controlled the distribution of coal seams and have significantly influenced mining operations throughout the region's history. The structural complexity includes numerous smaller-scale faults and fracture systems that create a mosaic of fault-bounded blocks [22].

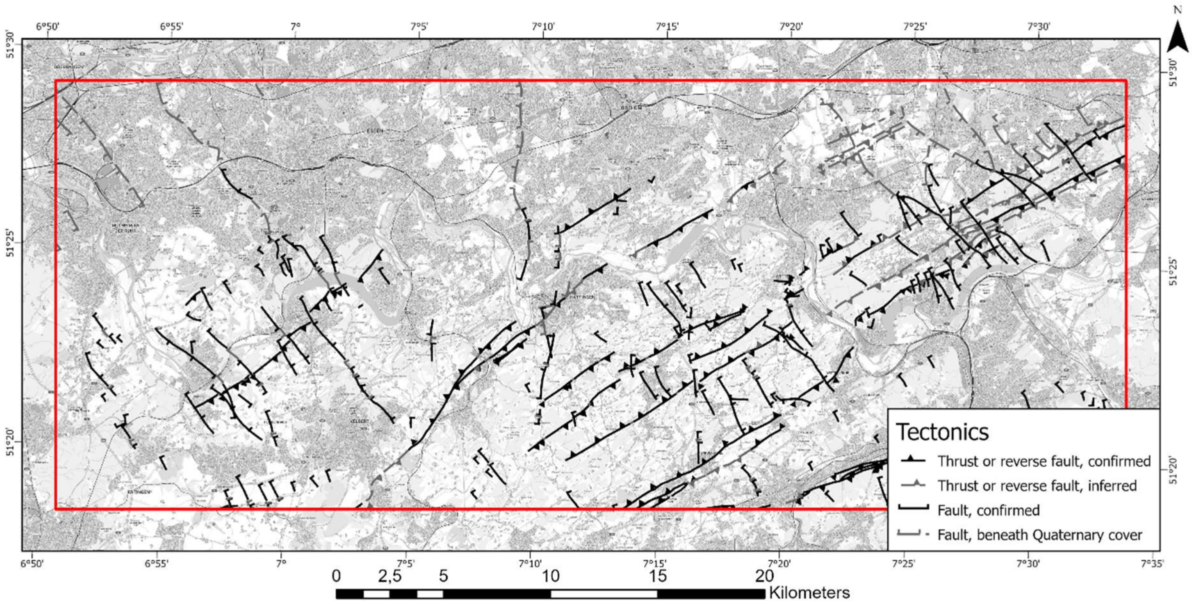

Figure 10: The local tectonics in the area are dominated by a system of NW-SE trending faults. Map data: [24].

Hydrology

The southern Ruhr Area is located within the drainage basin of the Ruhr River, which represents the main hydrographic axis of the region. The Ruhr River is a major right-bank tributary of the Rhine River and serves as the primary water supply source for the densely populated Ruhr metropolitan area. There are also various aquifers in the area (Figure 11).

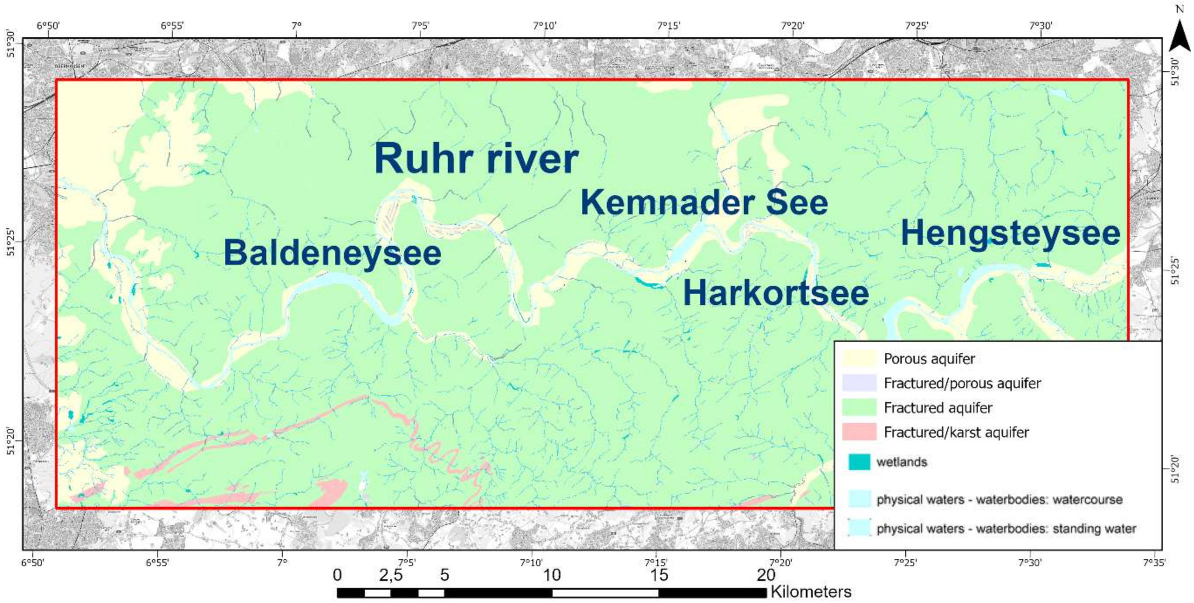

Figure 11: Hydrological network and aquifers in the study case area, dominated by the river Ruhr in the center. Map data: [13, 23, 27].

The Ruhr River flows in a generally westward direction through the southern part of the study area, with its course controlled by the underlying geological structure and modified by extensive engineering works including dams, weirs, and channelization. The river system includes numerous tributaries draining the surrounding upland areas, including the Lenne, Volme, and Ennepe rivers from the south, and smaller streams from the northern watershed [23].

The hydrographic network has been significantly modified by anthropogenic activities related to mining operations. Historical mining activities included extensive dewatering systems that fundamentally altered regional groundwater flow patterns. The cessation of active mining has led to ground- and mine-water rebound, creating new challenges for water management and infrastructure stability [16, 28].

<u>Surface Water Bodies</u>

Within the southern Ruhr Area, several significant surface water reservoirs serve multiple functions including water supply, flood control, and recreation (Figure 11):

- **Hengsteysee** (Lake Hengstey) - with an area of approximately 136 hectares, formed by the Hengstey Dam on the Ruhr River [29]
- **Harkortsee** (Lake Harkort) - with an area of approximately 137 hectares, created by the Harkort Dam [30]

- **Kemnader See** (Lake Kemnade/Lake Kemnader) - with an area of approximately 125 hectares, formed by the Kemnade Dam and completed in 1979, making it the youngest of the six Ruhr reservoirs [31]
- **Baldeneysee** (Lake Baldeney) - with an area of approximately 265 hectares, the largest reservoir in the study area [32]

Additional smaller water bodies include numerous former mining subsidence ponds, constructed wetlands, and recreational lakes created during post-mining landscape rehabilitation. These water features serve important ecological functions and provide recreational opportunities for the region's residents. The hydrographic network is supplemented by an extensive system of artificial waterways, including drainage canals, treated wastewater discharge channels, and mine water management systems.

3.1.2 Megalopolis lignite mine in Greece

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 [58].

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. Intercalated flysch sequences provide partial hydraulic barriers, compartmentalizing the karst system into distinct subsystems. The main karst aquifer covers an area of about 120 km^2, nearly half of which is exposed at the surface, and provides a major pathway for groundwater recharge and flow. Recharge has been estimated at around 45% of annual precipitation, and inflows from the aquifer have historically posed significant challenges to lignite mining. In the Kyparissia open pit, for example, three interconnected karst aquifers (main, north, and west) generated large water inflows that eventually led to the cessation of mining activities [59].

The lignite seams are of Plio–Pleistocene age and occur at shallow depths, enabling extensive surface exploitation since the 1970s. However, their direct hydraulic interaction with the karstic aquifer required continuous dewatering, and following mine closure, groundwater rebound processes have resulted in pit lakes, highlighting the strong geological and hydrogeological control of the basin.

Tectonics

The Megalopolis lignite basin is situated in a tectonically active region of the central Peloponnese. The basin lies in an intermontane depression bounded by significant mountain chains (such as Mainalo and Taygetos), and its structural configuration has been shaped by successive episodes of crustal extension, folding, faulting, and subsidence. Fault zones and fractures are pervasive in the carbonate bedrock, enhancing permeability and facilitating hydraulic connectivity between different karst units. These structural discontinuities also influence slope stability and deformation patterns, which are relevant for mine planning and long-term reclamation.

In Greece, seismicity is high and largely controlled by the interaction between the African plate and the Aegean (or Eurasian) system along the Hellenic subduction zone. The western Peloponnese, including the Megalopolis area, is considered to lie within a zone of moderate to high seismic hazard. Recent seismic hazard zonation [60] places the Peloponnese region among zones that correspond to stronger ground shaking potential.

Historical earthquake records confirm that the area has experienced moderate to strong seismic events: for example, a magnitude ~5.4 earthquake in 1966 affected Megalopolis and was felt with intensity VIII (Modified Mercalli) in the region.

According to the Greek seismic design standard (EAK 2000 / New Greek Seismic Code), all of Greece is partitioned into three seismic risk zones, each associated with a characteristic ground horizontal acceleration. Megalopolis falls under zone II in the code's table of inhabited areas. Under Zone II, the design spectral acceleration coefficient α is 0.16 (i.e., 0.16 g) for the basic seismic action.

Given the tectonic setting, the documented seismicity, and the regulatory requirements, the Megalopolis region must be treated as seismically active. For mining design, slope stability, structural support, pit walls and reclaimed areas, the potential dynamic loading and differential ground motion effects should be considered in geotechnical and structural analyses.

Hydrology

The hydrological and hydrogeological conditions of the Megalopolis basin are dominated by the interaction between mining voids and the karst aquifer system. During active lignite exploitation, continuous pumping was necessary to manage groundwater inflows, particularly in the Kyparissia open pit, where three interconnected karst aquifer systems (main, north, and west) discharged significant volumes of water into the mine [59]. These inflows ultimately led to the termination of lignite exploitation in this sector. Following the cessation of pumping, groundwater rebound processes have been observed, leading to the formation of pit lakes, such as the Kyparissia lake, which today has an average depth of about 30 m and a maximum depth of 36 m, covering an area of approximately 0.8 km^2. Fluctuations in the lake's water level are directly linked to groundwater level variations in the surrounding aquifers, highlighting the strong hydraulic connection between the two systems. In addition to groundwater dynamics, the surface hydrology of the basin plays an important role, as the Alfeios and Elissonas rivers traverse the area and have been diverted or modified to accommodate mining activities. Hydrochemical studies indicate that both groundwater and surface waters show evidence of interaction with mining-affected environments, with potential implications for water quality and post-mining land and water management [61].

3.2 Topography

3.2.1 Southern Ruhr Area in Germany

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 [24, 26, 27, 33-38]. 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 12).

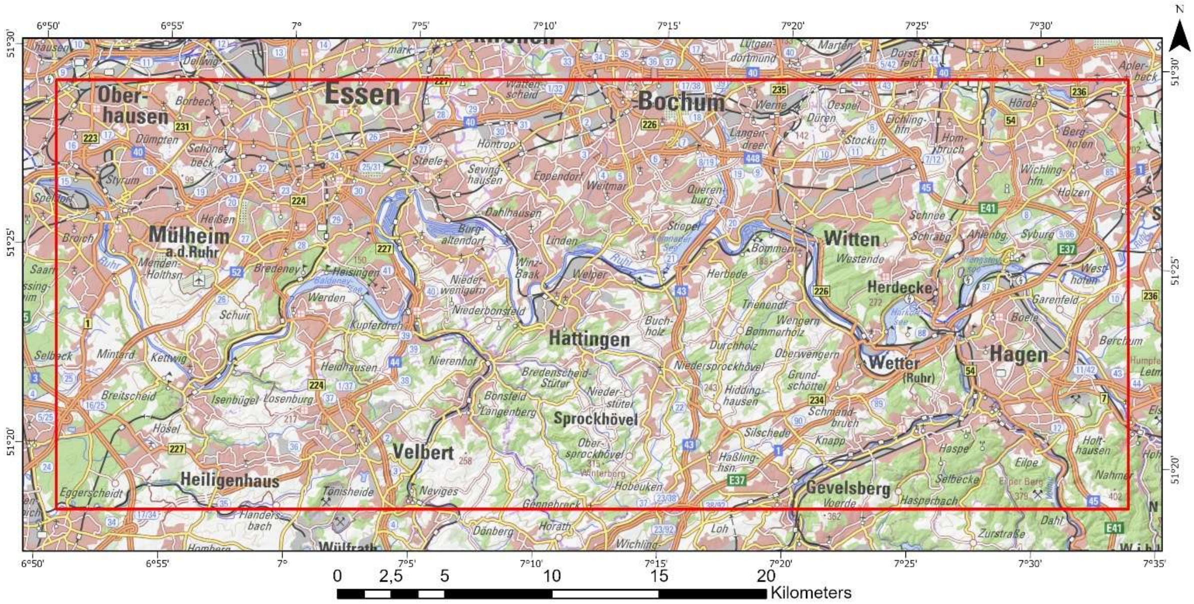

Figure 12: Combination of the digital topographic map 1:250,000 (DTK250) [39] and a relief shading [13] in the case study area.

<u>Elevation and Relief</u>

Hellweg Börden and Central Areas

The central zone of the study area is characterized by the Hellweg Börden, which form a gently southward-rising landscape terrace composed of Upper Cretaceous limestone. This Upper Hellweg Börde rises continuously from approximately 100 m above sea level in the north toward the Haarstrang in the south.

Emscher Lowlands

In the northern section of the area extends the Emscher lowlands as a flat depression zone with river valleys. Elevation differences here vary only between 55 m and 70 m above sea level. This landscape unit is characterized by Quaternary sediments and shows significant anthropogenic modifications due to centuries of mining activity.

Southern Ridges

The southern third of the area is dominated by the Ardey Hills and Haarstrang ridge. The Ardey Hills reach a maximum elevation of 273.8 m above sea level at the largely forested ridge "Auf dem Heil" near Herdecke. Other significant elevations include Klusenberg (254.3 m), Wartenberg (246.1 m), and Syberg (245.4 m).

The eastward-extending Haarstrang forms a prominent ridge running from west to east, typically reaching elevations of 200 to 250 m above sea level. It rises approximately 100 to 150 m above the Ruhr and Möhne valleys to the south and the Hellweg Börden to the north.

Drainage System and Hydrography

The Ruhr River forms a natural southern boundary of the area, flowing along the Ardey Hills into which it sometimes cuts with steep, rugged slopes. The Emscher traverses the northern sections as the primary watercourse, draining the Emscher lowlands. The Dortmund-Ems Canal begins at Dortmund's city harbor and leads northward.

Mining-Induced Relief Modifications

The study area exhibits significant mining-induced elevation changes [40]. The largest subsidence areas, reaching up to -25 m, occur in the central Emscher lowlands. Particularly pronounced are subsidence zones between urban areas, where net subsidences of several meters have been documented. These mining subsidences resulted from centuries of underground hard coal extraction through deep mining.

As counterparts to the subsidence areas, many spoil heaps shape the landscape as anthropogenic landforms. These artificial elevations sometimes reach considerable heights and represent prominent landscape elements that rise from the originally rather flat terrain [25].

<u>Landscape Character</u>

The relief shows a characteristic tripartite division: the flat to gently undulating Emscher lowlands in the north, the gently rising Hellweg zone in the center, and the distinctly more relief-rich southern ridges of the Ardey Hills and Haarstrang. This natural regional structure is overlaid by mining legacies in the form of subsidence areas and spoil heaps, creating a complex relief structure that combines both natural and anthropogenic landform elements. This division is also clearly visible in the satellite image (Figure 13).

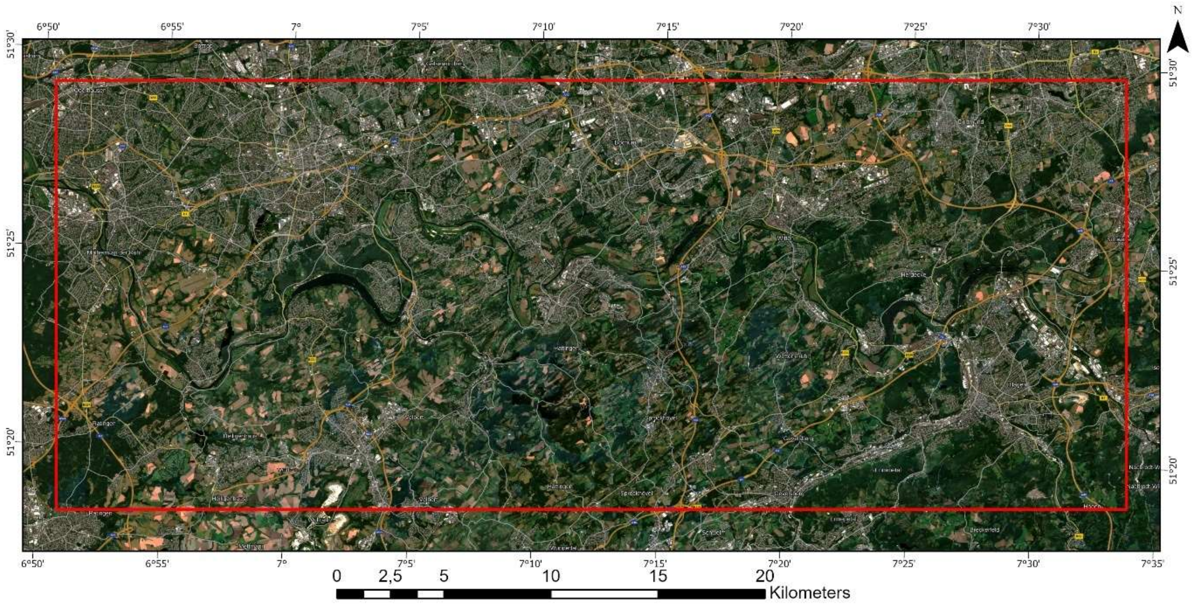

Figure 13: Sentinel-2 mosaic [41] and aerial image overlay [14] of the case study area

Slope gradients throughout most of the Ruhr area are generally low, with inclinations exceeding 10° occurring rarely. This enhances the perception of mining-induced relief changes, as both subsidences and spoil heaps appear particularly prominent in the largely flat landscape.

The area represents a typical example of an intensively modified industrial landscape where natural topographic features interact with substantial anthropogenic relief changes to create a unique post-mining topography characteristic of the southern Ruhr metropolitan region.

3.2.2 Megalopolis lignite mine in Greece

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 [62].

The Alfeios River and its tributaries, including the Elissonas, traverse the valley, draining it toward the northwest through the gorge of Karytaina. These rivers have shaped the hydrographic and geomorphological setting of the area, carving shallow valleys and providing natural outlets for surface water. The overall configuration of the basin is largely the result of tectonic subsidence and the accumulation of fluvial and lacustrine deposits, which have produced the relatively low-lying and soft relief of the central plain.

Anthropogenic activity has significantly transformed the original topography. Since the 1970s, extensive surface lignite exploitation has altered the land surface through the creation of large open pits, waste dumps, and artificial embankments (Figure 14). By the early 2000s, around 27 km^2 of land had been expropriated, with about 20 km^2 occupied by lignite fields and 8.5 km^2 by external waste deposits [57]. These interventions have left behind irregular landforms, including deep excavations, artificial mounds, and disturbed drainage paths. Together with the infrastructure of mining operations and the Public Power Corporation's power plants, these modifications have permanently reshaped the landscape of the basin.

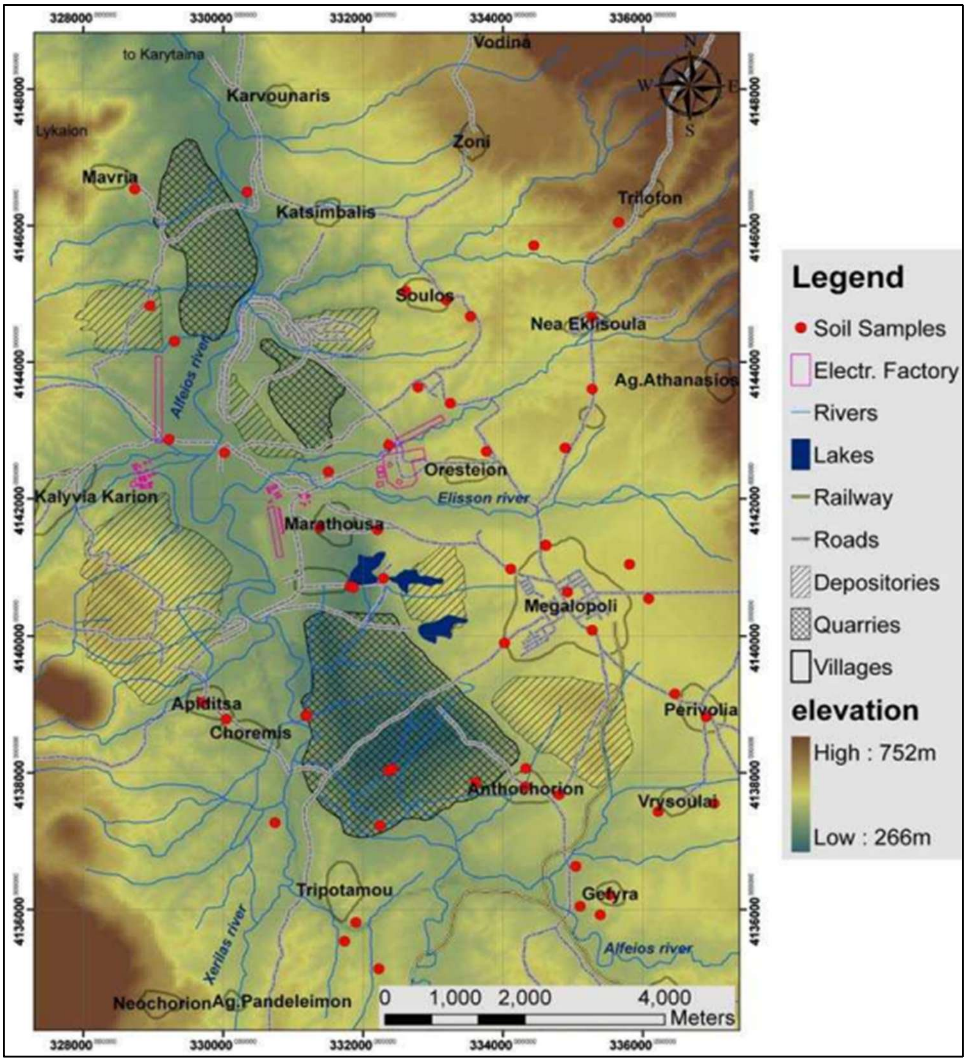

Figure 14: Topography map of Megalopolis showing the location of the town of Megalopolis, the installations of the power plant, the location of the quarries and depositories [63]

3.3 Mining methods

3.3.1 Southern Ruhr Area in Germany

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 [2, 42].

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 [2].

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 [2].

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 [2]. However, many of these centuries-old systems are still in operation today, passivly dewatering big areas in the southern Ruhr area [16]. The utilisation of steam engines also enabled the mining of deeper seams by constructing deeper shafts (Figure 15).

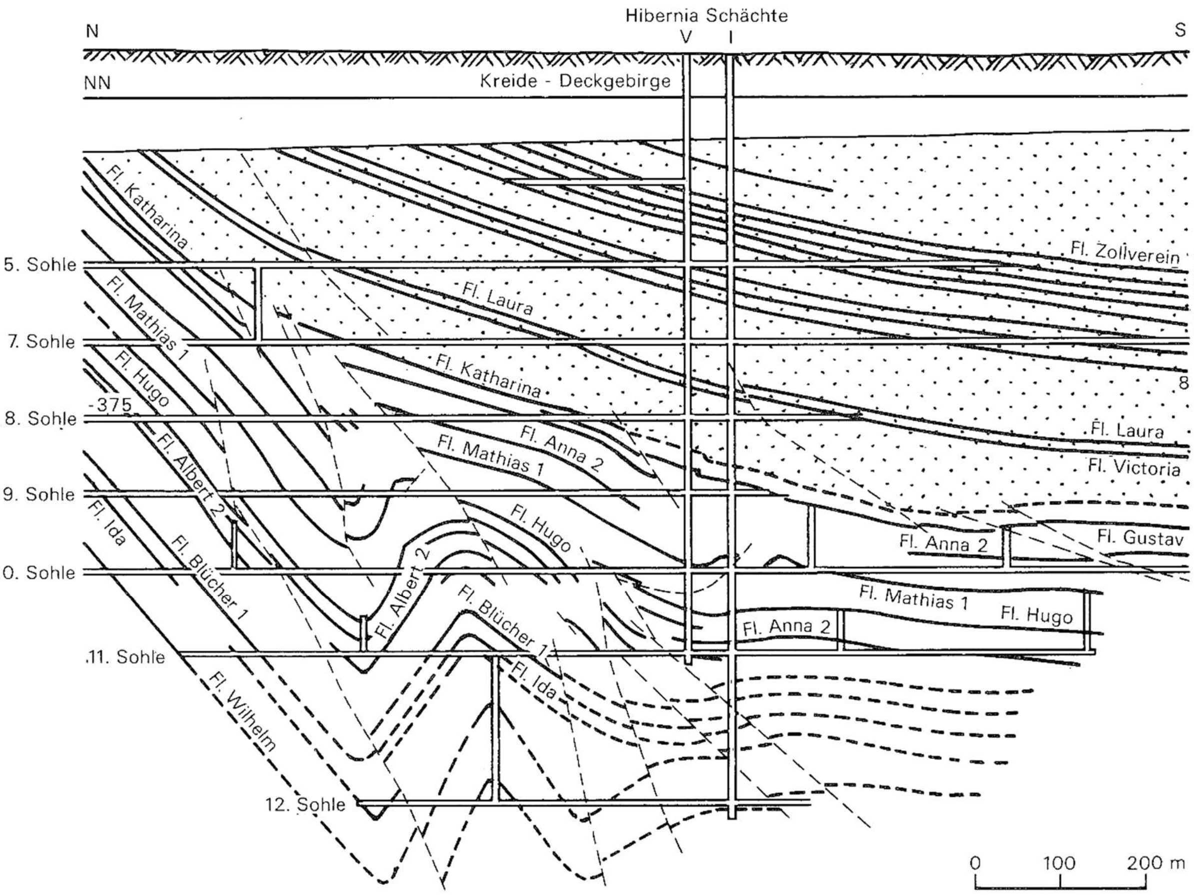

Figure 15: Example of coal mining (Hibernia colliery in Bochum) using shafts on several levels [22]. Different mining techniques were used depending on the location and inclination of the seams.

The room-and-pillar method (German: "Örterbau") was utilised in particular, both with and without backfilling, and adits and shafts were employed [2, 42]. 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 [20].

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 [2]. 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 [42]. 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.

3.3.2 Megalopolis lignite mine in Greece

Mining activity in the Megalopolis lignite basin began in the early 1970s with the operation of the Thoknia mine, which was depleted and closed by 1994. Since then, three major open-cast mines - Choremi, Marathousa, and Kyparissia - have formed the core of exploitation [57, 62]. Unlike the historical underground methods used in many European coalfields, lignite in Megalopolis has always been extracted through large-scale surface mining due to the shallow depth and horizontal layering of the deposits.

The method applied is continuous surface mining, which combines bucket-wheel excavators, conveyor belts, stackers, and spreaders in an integrated system. This allows for the simultaneous removal of overburden and lignite extraction, as well as the transport and deposition of waste rock in external or internal dumps. These continuous systems are complemented by non-continuous machinery, such as hydraulic excavators, loaders, and diesel-powered vehicles, which support selective excavation, auxiliary works, and internal transport.

Hydrogeological conditions have significantly affected mining practice. The presence of extensive karstic aquifers in the limestone basement required systematic dewatering and, in some cases, diversion of surface watercourses. The Alfeios River and its tributary Elissonas were partly diverted to protect the mines and ensure their safe operation [57].

Annual lignite production has historically reached 9-15 million tons, depending on demand from the adjacent Megalopolis power plants. To achieve this output, approximately 40 million m^3 of material (lignite plus overburden) were handled each year. Production is expected to decline progressively after 2028, with final exploitation projected to cease around 2040, followed by closure and rehabilitation works [57].

3.4 Number of mines/shafts/pits

3.4.1 Southern Ruhr Area in Germany

Due to centuries of mining, the exact number of mines, shafts and adits in the study area is unknown. Some areas were subject to smal 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 [43]. The number of undocumented cases is significantly higher.

The ongoing evaluation of mine maps held by the mining authority, which consist of drawings of mine workings created by miners, is expected to reveal a further increase in the total number of abandoned mine openings and the total area affected by residual mining cavities. Unfortunately, a significant number of mine maps were lost during the world wars, meaning the information on mining approved by the authorities is incomplete.

In addition to the documented mining, further mining has been carried out in North Rhine-Westphalia. The extent and scope of this additional mining is either barely known or completely unknown due to missing or insufficient documentation. This includes so-called 'ancient mining' (mining before mine maps were created) and illegal mining by third parties in times of need.

3.4.2 Megalopolis lignite mine in Greece

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 large-scale lignite exploitation, four major open pits have been developed: Thoknia, Choremi, Marathousa, and Kyparissia (Figure 16).

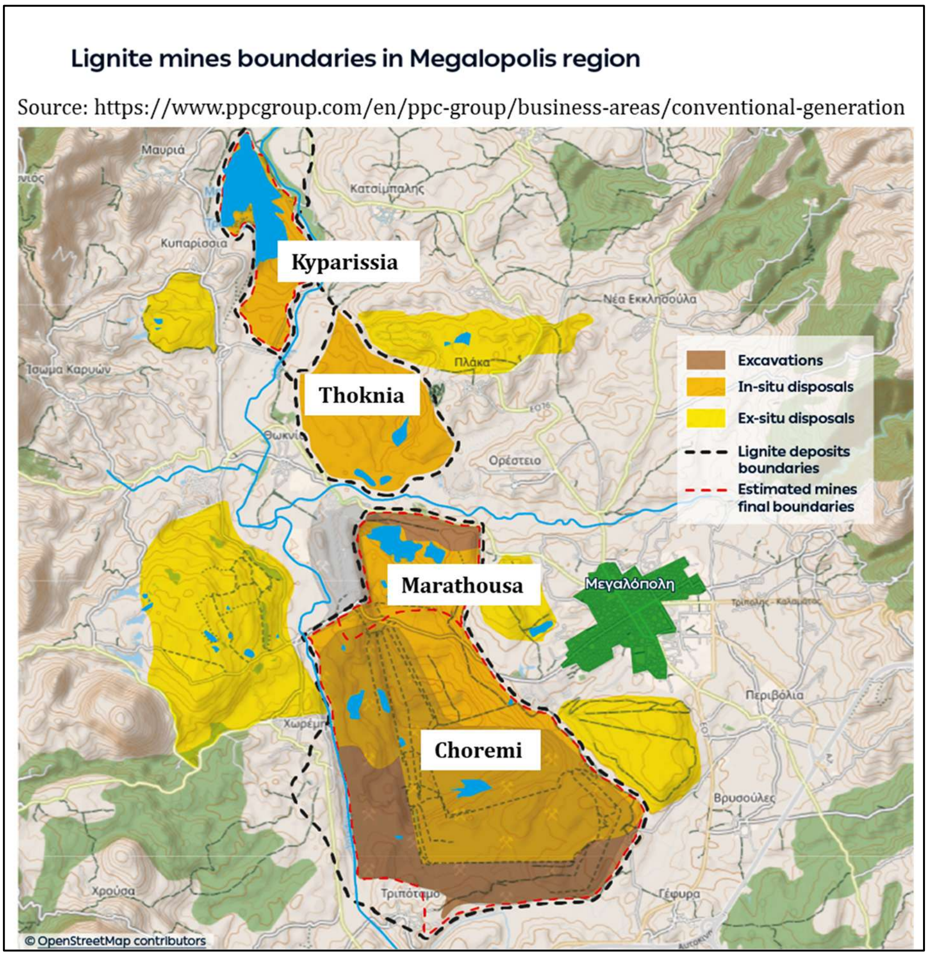

Figure 16: Megalopolis lignite mines' boundaries

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.

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.

3.5 Time of operation

3.5.1 Southern Ruhr Area in Germany

Coal mining started in the area possibly as early as the 12^{th} century [2], the first documented references date back to 1296 [25] and 1302 [2]. 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 [2]. 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.

3.5.2 Megalopolis lignite mine in Greece

The history of lignite exploitation in the Megalopolis basin is relatively recent compared to many European coal regions. Systematic mining began in the early 1970s, when the Public Power Corporation of Greece (PPC) opened the first large-scale open-pit, the Thoknia mine, to supply the newly constructed Megalopolis power plants. The development of mining was directly linked to the national energy strategy of Greece, since lignite served as the backbone of electricity production for several decades.

The Thoknia mine operated until 1994, when its reserves were exhausted. In parallel, the Choremi and Marathousa pits were developed and remained productive throughout the 1980s and 1990s, supplying millions of tons of lignite annually. The Kyparissia pit was also opened but encountered major hydrogeological challenges caused by inflows from the karst aquifer system, which made long-term exploitation unsustainable.

At the peak of activity, annual production from the Megalopolis mines reached between 9 and 15 million tons of lignite, with more than 40 million m^3 of overburden and lignite handled each year. Mining activity dominated the local economy and transformed large parts of the Megalopolis plain into active industrial and mining landscapes [57].

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.

4 Identification of the hazards

As part of WP2 and Deliverable D2.1, CERTH, with contributions from the project partners, developed a detailed database compiling all post-mining hazards that may occur in such areas. This database provides a comprehensive reference tool for experts and decision-makers, as it catalogues hazard types, mechanisms, and potential impacts. When hazard identification is conducted for a specific post-mining site, the database serves as the baseline, which can be complemented by historical data and the expertise of professionals familiar with the local conditions. This structured approach increases the accuracy and reliability of hazard detection.

Southern Ruhr Area in Germany

The identification and characterisation of post-mining hazards in the southern Ruhr area follows the comprehensive methodology developed within the POMHAZ project. This methodology is based on the knowledge created in prior work packages and tasks and has been validated through stakeholder consultation. The hazard assessment incorporates the expertise of other case studies and the regional knowledge of stakeholders who participated in the German POMHAZ workshop in June 2025 (Figure 17). Before and during the workshop, experts from the Research Centre of Post-Mining answered questions from participants about hazards, multi-hazard scenarios, elements at risk, and vulnerability factors for the test region. There were 35 participants who rated their own knowledge of the topics as an average of 80/100.

Figure 17: German POMHAZ Stakeholder workshop in June 2025

Only open geodata that provides homogeneous coverage for the entire study area was used for data collection to derive the hazard polygons (see

Table 1). In tests with individual stakeholders, finer-grained data sets were also successfully used for smaller test areas.

Table 1: Source of the analyzed raw data for the creation of hazard polygons

Hazard	Source of the raw data
Subsidence	RAG Bürgerinformationsdienst [44]
Sinkholes	GDU NRW [43]
Gas Emissions linked to Mining	GDU NRW [43]
Hydrological Disturbances	Historical maps and FZN analysis [16]
Environmental Pollution from Spoils	OSM, ADDISweb [15] [45]
Combustion and Overheating of Mine Waste	OSM, Wikipedia, ISBK50 [15] [26] [46]
Earthquake (Natural)	IS GDUEZ NRW [47]
Shallow Landslide (Natural)	Digital Elevation Model [14]
Rockfall (Natural)	Digital Elevation Model [14]
Flooding by Runoff and Mudslides (Natural)	Hochwasserkarten NRW [48]
Rainfall (Natural)	Hinweiskarte Starkregengefahren [39]

Megalopolis lignite mine in Greece

Each post-mining area is exposed to a variety of hazards that may differ in type, intensity, and spatial distribution depending on its geological, hydrological, and socio-economic characteristics. Within the POMHAZ project, hazard identification has been structured around three main categories: (i) post-mining hazards, (ii) natural hazards, and (iii) technological hazards. This categorization ensures that the full range of threats affecting post-mining regions is systematically addressed and incorporated into the risk assessment framework of WP3.

For natural and technological hazards, the project team collected and analyzed open-source governmental data, literature, and technical reports, ensuring a consistent and transparent methodology across case studies. The identified hazards and their preliminary evaluation were presented during internal POMHAZ meetings and at the workshop organized by CERTH in July 2025, where feedback from stakeholders and end-users confirmed the value of the findings.

Hazard identification constitutes the first step of the multi-hazard risk assessment method, which was evaluated in WP3 under Task 3.1. Table 2 presents the hazards identified within the POMHAZ framework together with the corresponding sources of raw data, which form the basis for their integration into the risk assessment framework as well as the GIS and DSS interface.

Table 2: Source of the analyzed raw data for the creation of hazard polygons

Hazard	Source of the raw data
Landslide (Generalized scale)	[54] [64] [66] [65] [53] [55]
Earthquake	https://oasp.gr/ http://www.geophysics.geol.uoa.gr/stations/gmapv3_db/index.php?lang=el
Fooloding	https://floods.ypeka.gr/ [56]
Rainfall	http://www.emy.gr/emy/el/

4.1 Mining hazards

4.1.1 Southern Ruhr Area in Germany

4.1.1.1 Subsidence

Ground subsidence is one of the most prevalent and persistent post-mining hazards in the southern Ruhr area. Stakeholder surveys rank it as the sixth most significant concern, with a score of 71/100. Subsidence occurs as a result of the gradual collapse or consolidation of underground voids created by coal extraction activities. This manifests as the continuous deformation of the ground surface, forming gentle, extensive depressions known as subsidence basins.

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. The heterogeneous nature of coal extraction in the region, which has spanned several centuries and employed various methods, has created a complex pattern of subsidence susceptibility.

The temporal evolution of subsidence varies significantly across the study area. While most subsidence associated with deep mining operations has stabilised following mine closure, areas above shallow historical workings continue to exhibit active deformation processes. The maximum recorded subsidence in comparable German coal mining regions is 25 metres, though values in the southern Ruhr area typically range from 0.5 to 8 metres.

4.1.1.2 Sinkholes

According to stakeholder assessment, sinkholes represent the highest-ranked hazard (score: 91/100), reflecting their sudden occurrence and potential to cause significant damage to infrastructure. Unlike gradual subsidence, sinkholes manifest as discontinuous deformations, characterised by the rapid formation of surface depressions, funnels or cavities.

Figure 18: Large sinkhole event in Bochum in the year 2000

In post-mining environments, sinkholes form through several processes: the direct collapse of underground voids; suffusion processes that leach sandy materials from overburden strata; and the deterioration of inadequately sealed mine shafts or galleries. The southern Ruhr area is particularly at risk in areas of shallow coal extraction and near historical mine openings. Developed empirically in the 1970s, the Hollmann/Nürnberg limit curves are used to assess the effects of surface mining. These curves show the maximum depth at which cavities can be formed without causing surface subsidence, depending on the dip of the mined seam, and they form the scientific basis for risk assessments. However, due to the limited documentation of historical mining in North Rhine-Westphalia, clear depth criteria were defined for hazard categorisation.

- Less than 30 metres of solid rock cover: High risk of sinkholes
- 30 to 100 metres: Medium risk of subsidence and sinkholes
- Over 100 metres: Low risk, with predictable subsidence primarily [68]. The mining authority counted 241 mining-related sinkhole events in the area from 2006 to 2022 [49] with an unknown number of unreported cases.

4.1.1.3 Gas Emissions Linked to Mining

Mine gas emissions, which were ranked by stakeholders as the 5th most significant hazard (with a score of 77/100), encompass the release of methane, carbon dioxide and other gases from abandoned underground workings. Gas generation and migration are controlled by several factors, including residual coal oxidation, the decomposition of organic materials within the mine environment and changes in groundwater conditions following mine closure.

In the southern Ruhr area, gas emission patterns are influenced by mine flooding and the subsequent rebound of groundwater. As water levels in abandoned workings rise, gases are displaced upwards through fracture systems, abandoned shafts and permeable overburden layers. This can lead to concentrated gas emissions at specific locations, particularly around inadequately sealed mine openings, in a phenomenon known as the 'piston effect'.

Monitoring requirements for post-mining gas emissions are regulated under German mining legislation, paying particular attention to methane concentrations that exceed safety thresholds. Due to the heterogeneous distribution of gas emission sources, site-specific assessment and monitoring strategies are required.

4.1.1.4 Hydrological Disturbances, mining induced floods (underground)

Hydrological disturbances, which have been given a stakeholder score of 80/100 for groundwater-related issues, are 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.

Mine water rebound following closure creates additional hydrological challenges. The rise of groundwater in abandoned workings, whether controlled or uncontrolled, can lead to changes in the water table extending several kilometres from mine sites. In extreme cases, uncontrolled mine water discharge can overwhelm natural drainage systems, resulting in surface flooding.

Centuries of mining activity have permanently altered the hydrological regime of the southern Ruhr area. Historical dewatering operations lowered regional groundwater levels by tens of metres, while mine closure and water rebound have created new equilibrium conditions. The interaction between mine water chemistry and natural groundwater systems poses further challenges for water quality management.

Centuries-old adits still play a crucial role in the area's current dewatering: If a blockage goes undetected, the water will find other ways to flow, which can have disastrous consequences (Figure 19).

Figure 19: Collapse in the mine workings of the over 150-year-old Edeltraut adit in the southern Ruhr area on February 5, 2026.

The dynamic pressure causes the plug to suddenly break away, resulting in an uncontrolled water outburst.

4.1.1.5 Environmental Pollution from Spoils

Environmental contamination from mining waste, particularly spoil heaps and tailings, is a major concern for stakeholders, with a score of 80/100. The southern Ruhr area contains numerous legacy mining waste sites, including overburden dumps, coal preparation waste and industrial residues from coal processing operations.

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. The heterogeneous composition of mining waste materials creates complex geochemical conditions that influence contaminant mobility and bioavailability.

4.1.1.6 Combustion and Overheating of Mine Waste

The spontaneous combustion of coal-bearing waste materials poses a continuous risk (score: 66/100), necessitating constant monitoring and management. This process involves the exothermic oxidation of residual coal in waste materials, which can lead to underground fires that persist for decades.

The development of fires is 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. Once established, underground fires are extremely difficult to extinguish and can compromise slope stability, air quality and groundwater conditions.

4.1.2 Megalopolis lignite mine in Greece

4.1.2.1 Slope movement (Generalized scale)

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, although not as deep as those in Northern Greece, frequently encounter stability challenges due to the relatively low shear strength of the marls and clays that overlie and interbed the lignite seams [64].

Landslides were reported in the Thoknia mine as early as the 1970s, underscoring the susceptibility of the deposits to failure when exposed to excavation and groundwater infiltration [65]. The hydrogeological setting further complicates stability: karstic aquifers and high groundwater inflows in areas such as Kyparissia have historically contributed to instability and, in some cases, led to premature cessation of mining activities. Slope instabilities in the Megalopolis mines typically manifest as large-scale deformations, progressive or regressive displacements, and, in some cases, compound failure mechanisms along weak clay-lignite interfaces. Rainfall events and water infiltration into fissured clay layers have been identified as critical triggering factors, as they reduce shear strength and elevate pore pressures. Case studies from the wider Greek lignite sector demonstrate that such movements may not always culminate in catastrophic collapse but can still cause significant operational and safety challenges (e.g., excessive displacements, bench heaving, and interruptions in production).

Given this context, slope movements are recognized as the most relevant post-mining hazard for Megalopolis [67] (Figure 20). Their identification aligns with both historical evidence and scientific analyses highlighting their persistence even after mine closure. Monitoring and integrating slope instabilities into the multi-hazard risk assessment is therefore essential, as these hazards threaten not only reclamation efforts but also the long-term safety and sustainability of the post-mining landscape.

4.2 Natural hazards

Following the July 2025 update to the sDSS, natural hazards could be included in the multi-hazard assessment alongside mining hazards. Unlike the mining hazards that have already been catalogued in WP2, these have not been ranked in the survey but have been added in the form of free text. These natural hazards differ fundamentally from post-mining hazards such as subsidence, sinkholes and gas emissions, and represent external triggers or concurrent processes that can interact with and amplify mining-related risks. The POMHAZ methodology specifically addresses these interactions through the multi-hazard assessment framework developed in Task 3.1.

4.2.1 Southern Ruhr Area in Germany

4.2.1.1 Earthquake

Seismic activity is natural ground motion caused by tectonic forces and is distinct from mining-induced seismicity. In post-mining areas, natural earthquakes can interact with compromised ground conditions, potentially triggering secondary hazards such as slope instability or structural failure in areas weakened by mining activities. According to regional geological surveys, the southern Ruhr area experiences low to moderate natural seismic activity, but the interaction with post-mining ground conditions requires careful evaluation.

4.2.1.2 Shallow Landslide

Natural slope failures are caused by gravitational forces acting on unstable slopes and are usually triggered by heavy rainfall, changes in groundwater levels, or seismic activity. In post-mining environments, altered topography, modified drainage patterns and artificial slopes created by spoil heaps or altered terrain can amplify natural landslide processes. The interaction between natural slope processes and landscapes modified by mining creates complex hazard scenarios that require an integrated assessment approach.

4.2.1.3 Rockfall

Natural rockfall events involve the detachment and movement downslope of rock fragments from steep rock faces or outcrops. In the southern Ruhr area, the risk of natural rockfall is generally low due to the relatively gentle topography. However, it can still occur along river valleys, quarry faces or natural escarpments. This hazard is exacerbated by mining-induced ground instability or artificial steep slopes created by mining activities.

4.2.1.4 Flooding by Runoff and Mudslides

Natural flooding is caused by extreme rainfall events that exceed the capacity of drainage systems, whether natural or artificial. This hazard encompasses surface water flooding caused by intense rainfall, as well as debris flows (mudslides), which occur when saturated soils become mobilised on slopes. In post-mining areas, natural flooding patterns are significantly altered by subsidence basins, changed topography and modified drainage networks, creating complex flood risk scenarios that differ substantially from those in the pre-mining era.

4.2.1.5 Rainfall

Extreme precipitation events are the main natural trigger of multiple cascading hazards in post-mining environments. Heavy rainfall directly affects slope stability, groundwater recharge and surface flooding, and can trigger various mining-related hazards through infiltration processes. The interaction between natural precipitation patterns and post-mining ground conditions creates unique vulnerability patterns that require specialised assessment methodologies. Projections of climate change indicate potential increases in the intensity and frequency of extreme precipitation, adding temporal complexity to hazard interactions.

4.2.2 Megalopolis lignite mine in Greece

4.2.2.1 Earthquake

The Megalopolis basin lies in a region of moderate to high seismicity associated with the Hellenic arc system. Seismic activity results from the convergence of the African and Eurasian plates, with the western and central Peloponnese frequently experiencing earthquakes of magnitude 5.0-6.0. Historical events confirm this hazard: the 1965-1966 earthquake sequence reached intensity VIII (MMI), causing damage in Megalopolis and nearby towns. According to the Greek Seismic Code (EAK 2000, revised in 2003), Megalopolis is classified in Seismic Zone II, corresponding to a design ground acceleration of 0.16g, highlighting a non-negligible hazard for infrastructure and reclaimed mine areas.

In a post-mining context, earthquakes are of particular concern because ground shaking may reactivate slope instabilities in open pits or waste dumps, destabilize embankments, or affect future reclamation structures. Seismic hazard maps and epicenter catalogues demonstrate that the Megalopolis region remains vulnerable to moderate but potentially damaging earthquakes . This justifies the inclusion of earthquakes as a key natural hazard in the POMHAZ framework. Figure 20 integrates seismic epicenter data with other hazards to provide a spatial overview of Megalopolis post-mining area seismicity.

4.2.2.2 Flood

Flooding is another significant natural hazard in the Megalopolis basin due to the presence of the Alfeios River and its tributary, the Elissonas. The basin's low-lying morphology, surrounded by mountain ranges, enhances flood susceptibility. Historical flood events have affected settlements and agricultural land, while mining operations have modified drainage networks, diverting rivers and altering natural runoff patterns .

In the post-mining stage, flood risk is expected to intensify. Large excavations may function as artificial reservoirs, and the rebound of groundwater following the end of dewatering operations could lead to the formation of pit lakes. External waste dumps and embankments may also alter hydrological pathways, increasing the probability of localized inundation. These processes highlight the close relationship between mining-induced modifications and hydrological hazards.

Flood-prone areas in Megalopolis have been delineated using open-source governmental data and hydrological studies of the Alfeios catchment. The hazard is considered both as a direct threat to communities and as an interacting factor that can trigger slope movements or amplify their consequences. A combined hazard map will illustrate potential flood zones alongside other threats (Figure 20).

4.2.2.3 *Rainfall*

Rainfall is a critical natural hazard in Megalopolis, acting both independently and as a trigger for slope instability and flood. The basin experiences intense rainfall events, particularly in autumn and winter. These episodes contribute to surface runoff, erosion, and groundwater infiltration. Rainfall infiltration reduces the shear strength of clayey and marly layers overlying lignite seams, elevating pore pressures and often triggering slope movements in active and abandoned pits .

Several slope failures recorded in the Megalopolis mines have been linked to intense rainfall episodes, demonstrating the hazard's practical importance. While not always catastrophic, rainfall-induced instabilities can disrupt mining operations, complicate reclamation works, and compromise safety. In the post-mining period, rainfall remains a concern, as it can erode dump slopes, undermine reclamation structures, and affect the stability of pit lakes and embankments.

Given projections of increasing frequency of extreme precipitation in southern Europe under climate change scenarios, rainfall hazard is expected to remain highly relevant for Megalopolis. Identification of this hazard within POMHAZ is supported by open-source meteorological datasets, recorded landslide inventories, and literature evidence linking rainfall with slope failures.

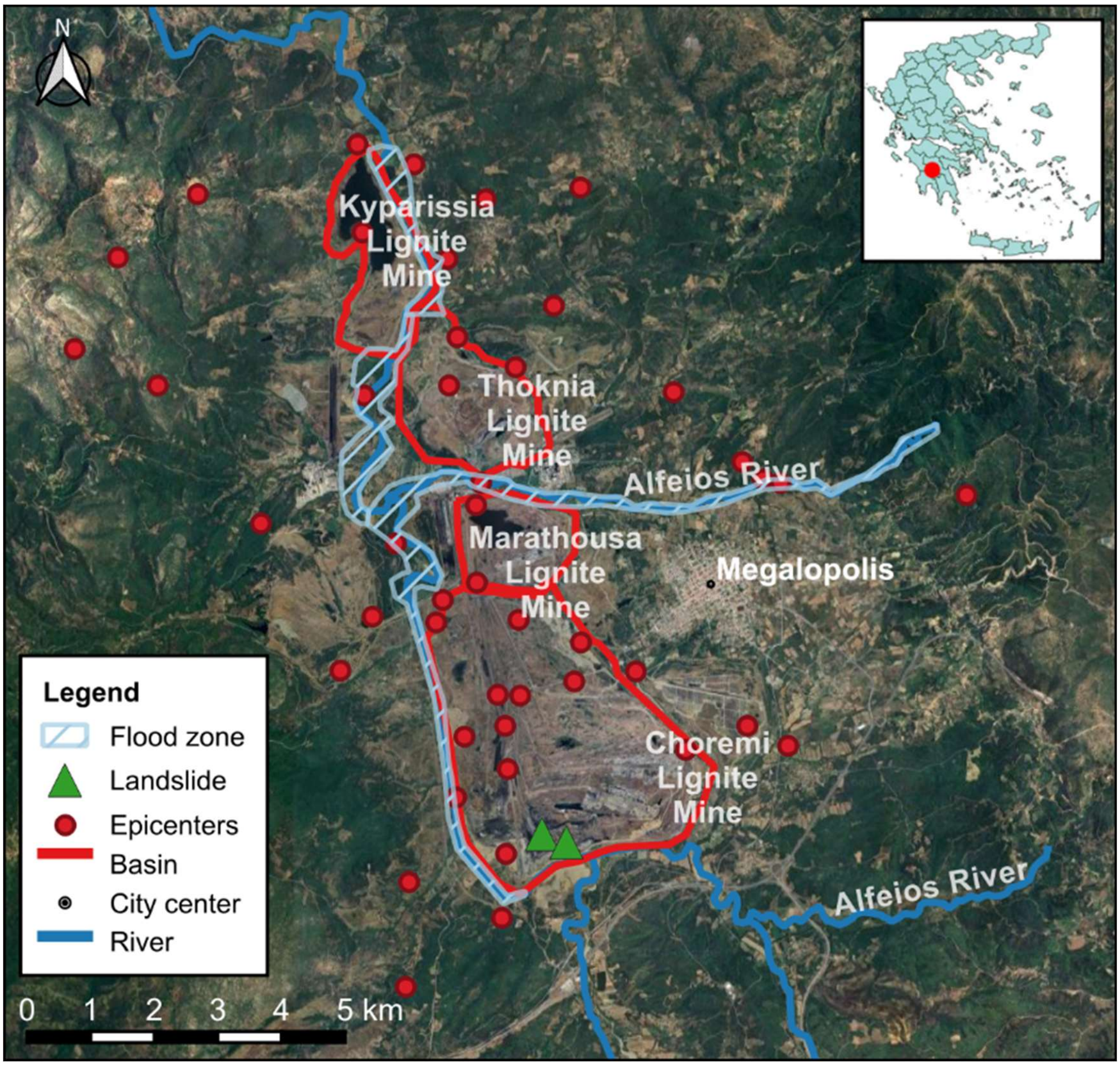

Figure 20: Megalopolis multi-hazard map [67]

4.3 Interaction between hazards, potential scenarios and calculation of the multi-hazard index

Once individual hazards have been identified in a post-mining area, it is essential to examine their potential interactions in order to capture the multi-hazard conditions. Hazards rarely occur seperately; instead, they often influence or trigger one another, leading to cascading effects or compounding impacts that can significantly increase the overall risk. For example, in post-mining environments such as Megalopolis, heavy rainfall may trigger slope movements or intensify flooding, while seismic activity can destabilize slopes or damage reclamation structures, thereby amplifying the consequences of other hazards.

Within the POMHAZ project, the systematic assessment of hazard interactions was first introduced in Task 2.3, where the concept of the interaction matrix was applied to the selected case studies. This tool provides a structured method to evaluate how different hazards may influence each other. The outcomes of this task laid the foundation for its integration as a core component of the multi-hazard risk assessment framework in T3.1.

The interaction matrix is filled using a combination of information sources: scientific literature that documents known hazard linkages, historical records of past events in the study areas, and the expert judgement of the project partners. This triangulated approach ensures that both empirical evidence and site-specific expertise inform the evaluation of interactions. Once completed, the interaction matrix allows the definition of potential multi-hazard scenarios, which represent realistic combinations of hazards occurring either sequentially or simultaneously.

These scenarios are then quantified through the calculation of the Multi-Hazard Index (MHI), which synthesizes the identified hazards and their interactions into a numerical value. The MHI provides a comparative measure of the relative severity of different multi-hazard scenarios and forms a key input for the subsequent steps of the risk assessment and decision-support process.

As outlined in the POMHAZ proposal, a notable innovation in the development of the DSS tool for post-mining hazard assessment and risk management is the incorporation of artificial intelligence (AI) and machine learning (ML) techniques. The direct implementation of cutting-edge AI systems was not a viable option due to the rapid pace of development in this field, as well as issues pertaining to licensing and computing power. As an alternative option, in the Ruhr area use case, an advanced and secure AI tool from THGA incorporating different state-of-the-art LLM and reasoning models was used to test the automatic creation of the necessary interaction matrix. The data set was comprised of all available hazard data, survey responses, literature research, expert knowledge and prior reports and publications from the POMHAZ project. The resultant matrix (Figure 21) was found to be congruent with the manually created interaction matrix from the THGA scientists. This matrix illustrates the potential interactions between various post-mining and natural hazards within the study area, and will be utilised for further analysis in the sDSS. For the case study of Megalopolis post-mining area, an interaction matrix was developed using the information presented in the previous subsection regarding hazard occurrence, complemented by the expert judgement of the project partners and will be further analysed in the sDSS (Figure 22).

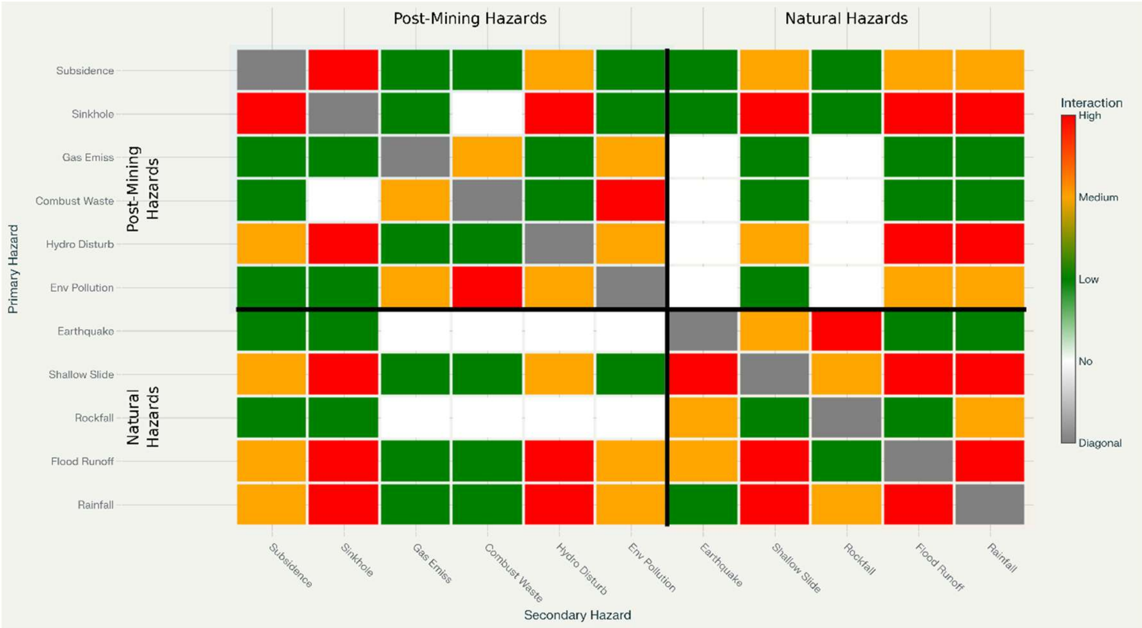

Figure 21: Interaction matrix for the Ruhr Area case study corporating post-mining and natural hazards

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

Figure 22: Interaction matrix for the Megalopolis area corporating post-mining and natural hazards

5 Identification of elements at risks

The Southern Ruhr case study area is highly populated on the northern parts with many elements at risk. In case of the Megalopolis post-mining area the elements at risk are close to the city of Megalopolis. Using the POMHAZ and sDSS methodology, Land Use/Land Cover data derived from Sentinel-2 data [50] was employed (Southern Ruhr Area in Figure 23 and Megalopolis post-mining area in Figure 24) and reclassified from 1 (lowest risk) to 9 (highest risk). The following normalization was used (Table 3):

Table 3: EAR-level based on the Land Use / Land Cover

LU/LC	Water	Trees	Flooded vegetation	Crops	Built area	Bare ground	Snow/Ice	Rangeland
EAR	2	3	2	4	8	2	1	4

The result of the reclassification is shown in Figure 25 for the Southern Ruhr Area and in Figure 26, highlighting higher risks for elements on the surface in denser populated areas.

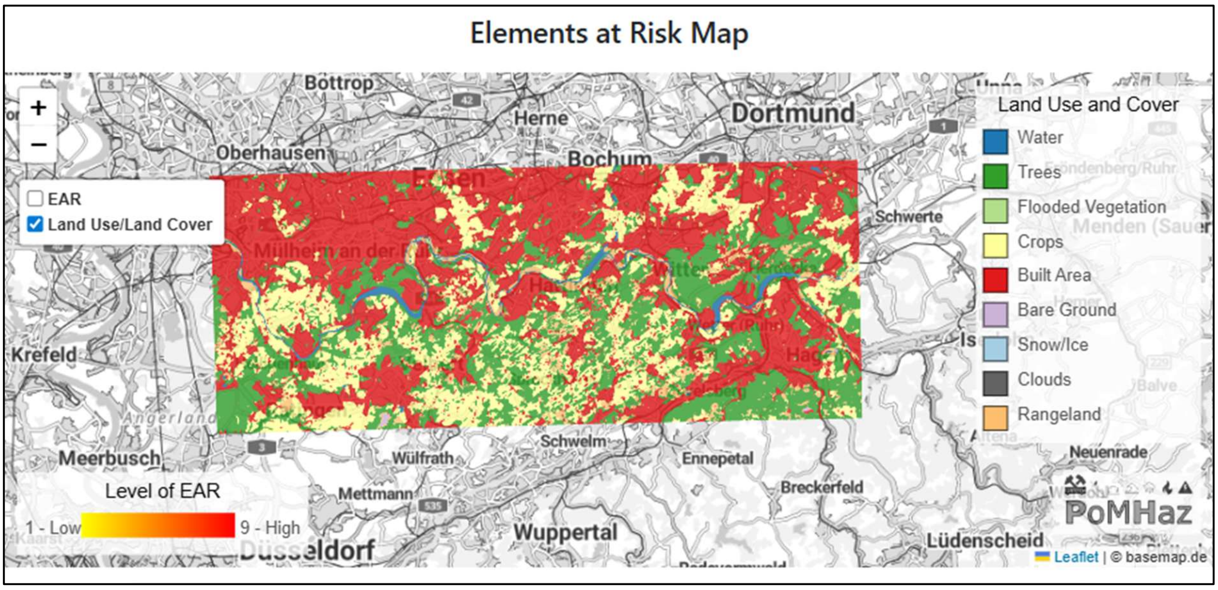

Figure 23: Land Use / Land Cover in the Southern Ruhr case study area

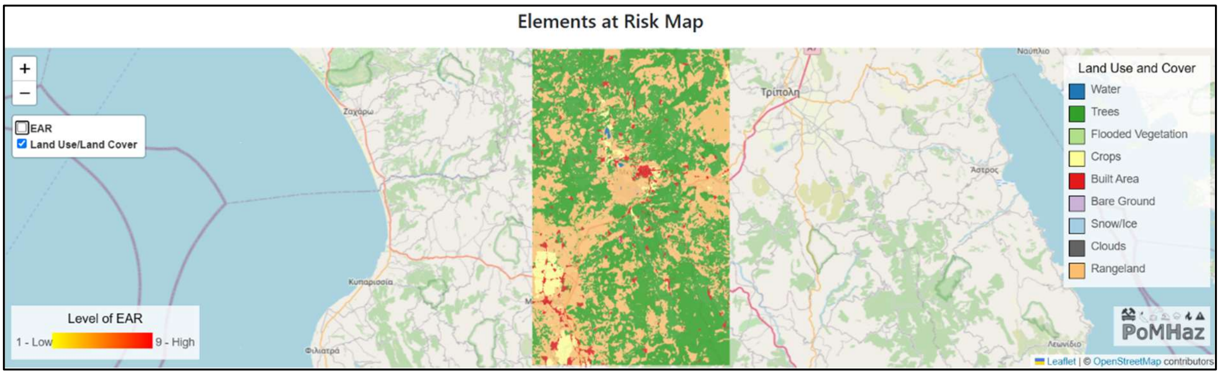

Figure 24: Land Use / land Cover in the Megalopolis case study area

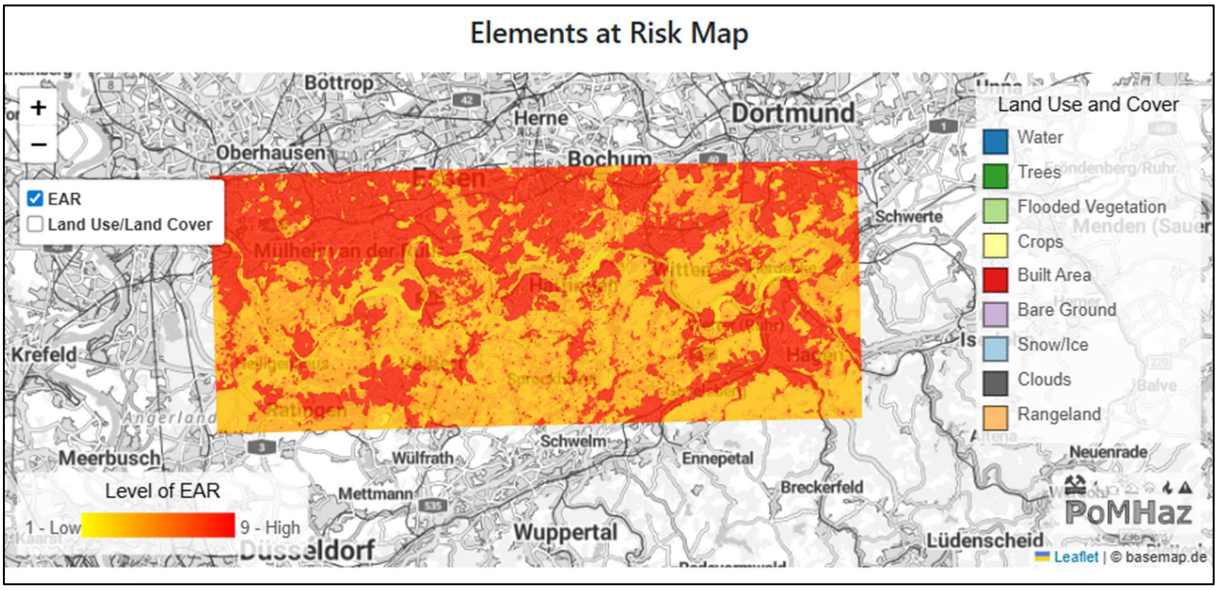

Figure 25: Reclassified EAR value in the Southern Ruhr case study area

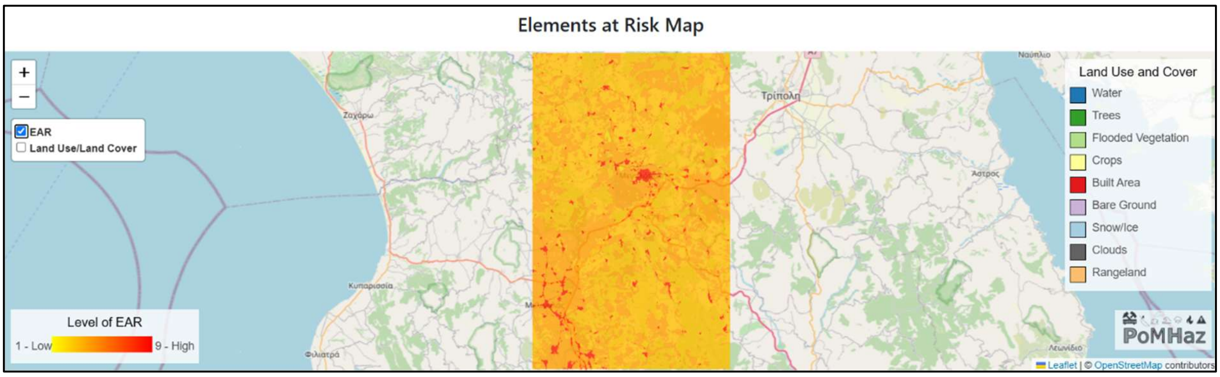

Figure 26: Reclassified EAR value in the Megalopolis case study area

6 Identification of Vulnerability factors

6.1 Southern Ruhr Area in Germany

The calculation of the VI utilizing the four classes was conducted for each municipality within the AOI, representing the lowest data resolution available. Open data [5, 15] allowed for the gathering of values for each subclass, which were then normalized from 1 to 9 in comparison to national averages. The class value was calculated as the mean of the subclasses, weighted and used as a factor for the overall VI calculation. Table 4 shows the values for the cities in the case study AOI, while Figure 27 provides a visual representation of this data.

Table 4: Calculation of the VI for different cities in the AOI using open data and the standard weights

City	Socioeconomic factor	Household factor	Environmental factor	Infrastructure factor	Vulnerability Index (VI)
Bochum	5,5	7	5	3,5	**5,65**
Breckerfeld	4	4	5	3,125	**3,925**
Dortmund	6	7	5	3,5	**5,8**
Ennepetal	4,5	5,5	4	3,125	**4,575**
Essen	6	7	5	3,25	**5,75**
Gelsenkirchen	6,5	7	5	3,5	**5,95**
Gevelsberg	4	6	5	3,375	**4,775**
Hagen	6	3,5	1,5	3,175	**3,985**
Hattingen	4,5	6	3,5	3,125	**4,725**
Heiligenhaus	4	6	5	3	**4,7**
Herdecke	3,5	6,5	4	3,375	**4,725**
Mülheim a. d. R.	5	6,5	5	3,25	**5,25**
Oberhausen	7	7	5	3,5	**6,1**
Ratingen	3,5	6	5,5	3	**4,6**
Schwelm	4,5	6,5	5,5	3,375	**5,175**
Schwerte	4	5,5	5	3,375	**4,575**
Sprockhövel	3,5	6	5,5	3,125	**4,625**
Velbert	4,5	6	4,5	3	**4,8**
Wetter (Ruhr)	4	5,5	4	3,125	**4,425**
Witten	5	6	5	3,25	**5,05**
Wülfrath	4	6	4,5	3,125	**4,675**
Wuppertal	6	7	5	3,425	**5,785**

As expected for a region affected by decades of mining, the socioeconomic, household and environmental factors in this region are below the national average. However, the region's infrastructure is a significant advantage, as it can facilitate the post-mining transition process.

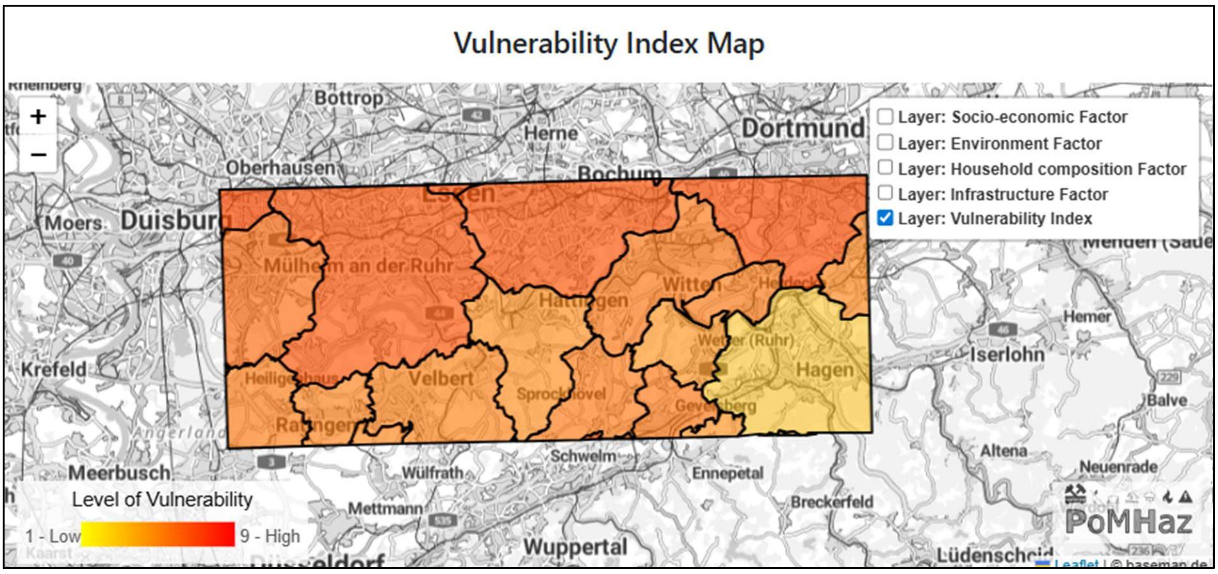

Figure 27: VI value in the Southern Ruhr case study area

6.2 Megalopolis lignite mine in Greece

The assessment of vulnerability in the Megalopolis post-mining area follows the methodology of the vulnerability index, which was evaluated and applied within the POMHAZ multi-hazard risk assessment framework during WP3. Vulnerability in this framework is conceptualized as the combination of social and physical components, reflecting both the sensitivity of local communities and the resilience of the built and natural environment to multi-hazard events. The vulnerability index provides a balanced view of the exposure and sensitivity of Megalopolis to multi-hazard scenarios by integrating multiple aspects of human, environmental, and infrastructural conditions.

To ensure comparability, the indicator values were normalized on a scale from 1 to 9, with higher values corresponding to greater vulnerability. The weighting of the four categories is fixed through the spatial Decision Support System (sDSS) interface, which provides consistency across case studies and ensures that the results can be integrated into the GIS-DSS platform.

The calculation of the vulnerability index for Megalopolis is therefore based on a structured and transparent process, combining quantitative data with a well-defined methodological framework. In the following, the procedure through which each indicator value was determined is described in detail, providing the basis for the overall vulnerability assessment of the post-mining area.

Socioeconomic status	Description
Below poverty (v_1)	Megalopolis is situated in the Peloponnese region, which, in 2023, recorded the highest rate of people at risk of poverty in Greece at 35.7%
Gross Domestic Product or GDP per person in the area (v_2)	Megalopolis is situated in the Peloponnese region - NUTS 2 level, data from 2022: GDP per capita of approximately 18145€

Household composition	Value
Population under 17 y.o. and over 65 y.o. (v_3)	The town of Megalopolis had a population of 5344 residents, data from 2021: The population under 17 y.o. and over 65 y.o. is approximately 34%.
Population density (people/ km^2) (v_4)	The municipality of Megalopolis had a population of 8784 residents spread over an area of 722.9 km^2, resulting in a population density of approximately: 12.15 people per km^2

Environment	Value
Settlement Area (v_5)	Estimated settlement area = modern town + surrounding inhabited zones: ≈10–15 km^2 (based on satellite imagery) Settlement Area (%): Using an approximate settlement area of 12 km^2 Settlement Area ≈1.66%
Urban and agricultural areas (v_6)	Land use composition (from EU CORINE Land Cover and regional studies): Urban/built-up areas: ≈10–15 km^2 → 1.66% Agricultural land: ≈200–250 km^2 → 31.1% Urban and agricultural areas = 32.76%

Buildings and transportation	Value
Age of building (v_7)	60% before 1980 → Age ≈ 2025 - 1970 = 55 years 25% 1980–1999 → Age ≈ 2025 - 1990 = 35 years 15% after 2000 → Age ≈ 2025 - 2010 = 15 years Average Age=(0.60×55)+(0.25×35)+(0.15×15)= 44 years
Material of building (v_8)	The majority of buildings in Megalopolis are constructed with reinforced concrete, the most common after 1960.
Geometry (v_9)	In Megalopolis, most buildings have simple, regular geometries, typically rectangular or square layouts with one or two stories.
Traffic area (v_{10})	In municipalities like Megalopolis, traffic infrastructure (urban streets, rural roads, small highways) usually covers about 2–3% of the total land area. Traffic Area ≈2.5%

Indicators	Value	Factor
Below poverty (v_1) (%)	35.7	8
Gross Domestic Product or GDP per person in the area (v_2) (€)	18145	7
Population under 17 y.o. and over 65 y.o. (v_3) (%)	34	2
Population density (v_4) (people/ km^2)	12.15	1
Settlement Area (v_5) (%)	1.66	2
Urban and agricultural areas (v_6) (%)	32.76	3
Age of building (v_7) (years)	44	5
Material of building (v_8)	RC	1
Geometry (v_9)	simple	2
Traffic area (v_{10}) (%)	2.5	2

7 Application of the case study using DSS-GIS tool

Following the comprehensive hazard identification, characterisation and interaction analysis described in previous sections, the POMHAZ Spatial Decision Support System (sDSS) was applied to the case study of the southern Ruhr area and Megalopolis post-mining area to demonstrate its operational capabilities and validate the multi-hazard assessment methodology. This involved utilising all available datasets, including geological and hydrological information, historical mining records, infrastructure databases, demographic data and comprehensive stakeholder survey results from 35 regional experts.

7.1 Southern Ruhr Area in Germany

The sDSS application process integrated the stakeholder survey findings, which identified the highest-priority post-mining hazards for the southern Ruhr area (sinkholes scoring 91/100, flooding/precipitation events 80/100, and environmental contamination 80/100), with the systematic hazard interaction analysis that revealed 85.5% interconnectedness between identified hazards. Expert knowledge from the Research Centre of Post-Mining (FZN) at THGA, combined with the established interaction matrix methodology, guided the selection of three representative test scenarios that collectively address the most critical multi-hazard combinations while testing different functional aspects of the sDSS.

Shown in the interaction matrix, many possible multi-hazard scenarios are possible in the region. From these, three application scenarios in the southern Ruhr area (Figure 28) were specifically chosen to validate the sDSS performance across different temporal scales (immediate response, progressive development, and long-term evolution), hazard interaction complexity levels, and decision-making contexts (emergency management, environmental protection, and long-term planning). Each scenario demonstrates specific capabilities of the sDSS while addressing practical risk management challenges identified through the stakeholder consultation process.

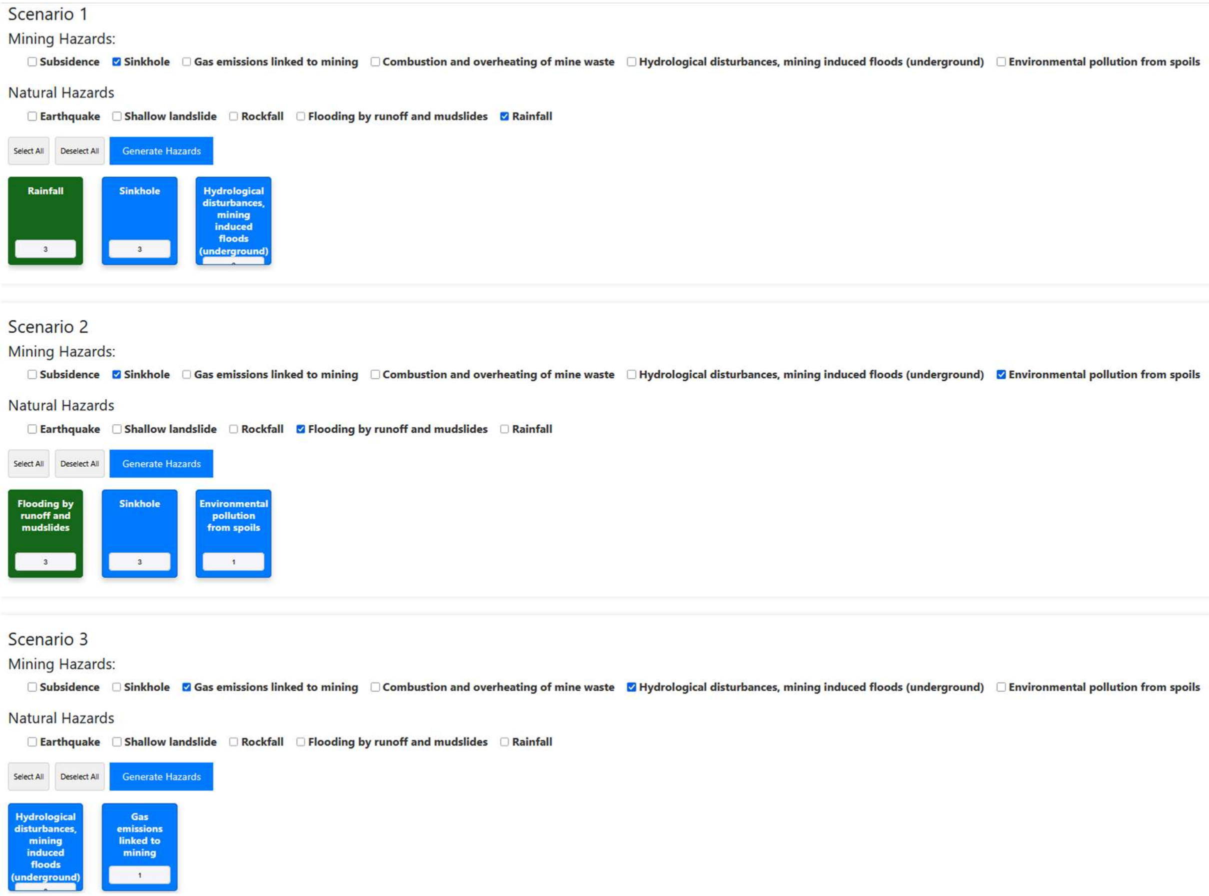

Figure 28: The three scenarios for testing the different sDSS capabilities

Scenario 1: Precipitation-Triggered Multi-Hazard Response Test

The first application scenario implements the highest-priority interaction pathway identified through stakeholder assessment: Rainfall → Sinkhole Formation → Hydrological Disturbances. This scenario was selected to test the sDSS capability for rapid-onset hazard assessment and emergency response support, addressing the most immediate and high-consequence multi-hazard situation facing the southern Ruhr area. The results are show in Figure 29.

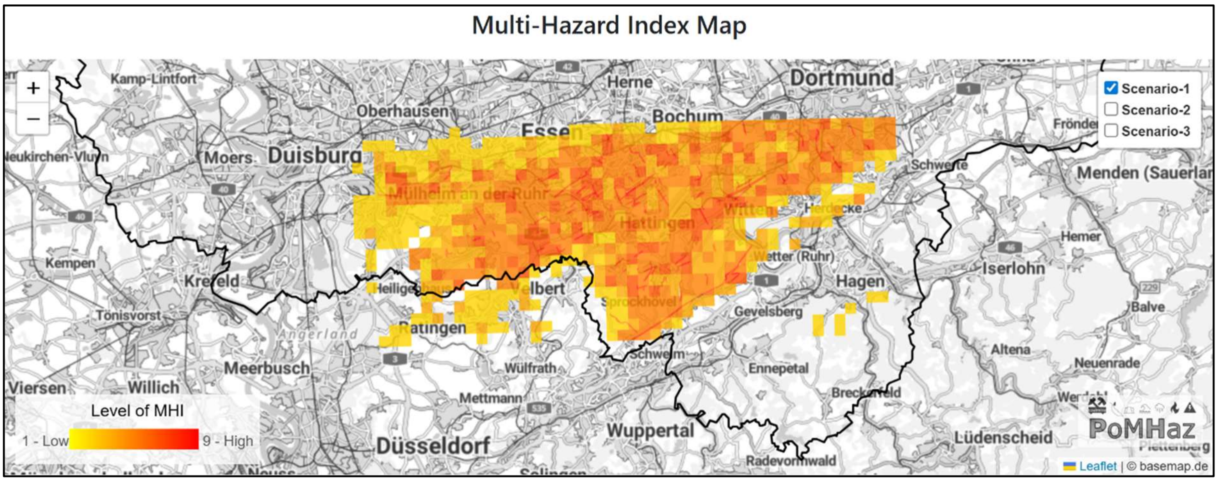

Figure 29: The sDSS Multi-Hazard Index Map for the first test scenario

Application results demonstrate successful integration of heterogeneous datasets within operationally relevant timeframes (risk assessment completion within minutes after scenario activation). The sDSS correctly identifies known high-risk areas validated against historical sinkhole occurrence patterns while providing actionable information for emergency management coordination. System performance testing confirms capability to support decision-making under time-constrained emergency conditions typical of precipitation-driven hazard events.

Scenario 2: Environmental Contamination Pathway Assessment

The second scenario implements the Flooding by Runoff → Sinkhole Formation → Environmental Pollution interaction pathway, testing sDSS capability for environmental risk assessment and contamination response planning. This scenario addresses stakeholder concerns about long-term environmental consequences of multi-hazard interactions and validates system performance for environmental management applications. The results are shown in Figure 30.

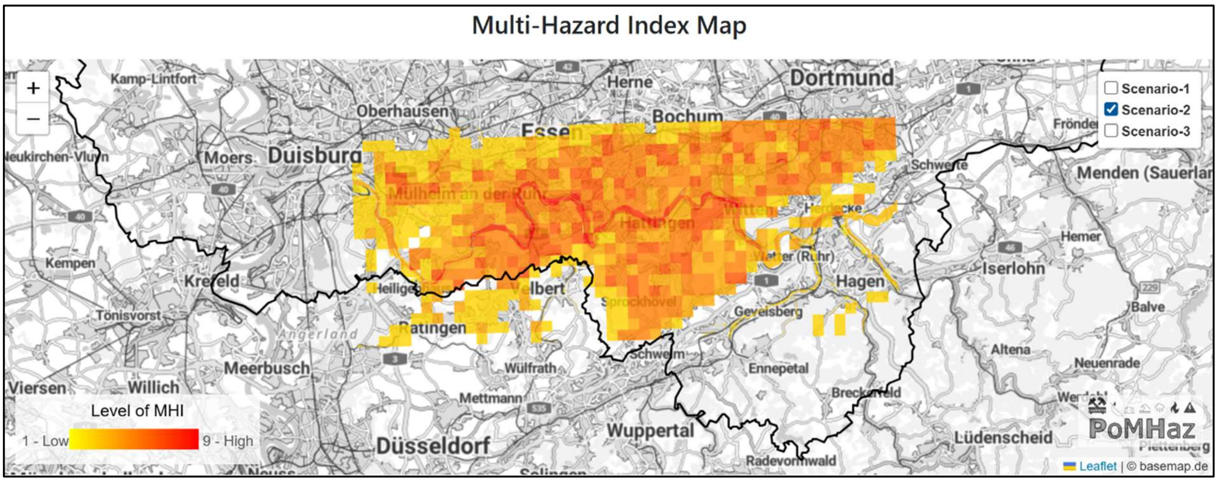

Figure 30: The sDSS Multi-Hazard Index Map for the second test scenario

Application testing validates sDSS capability to generate accessible risk communication materials for diverse stakeholder audiences including municipal governments, environmental agencies, emergency services, and affected communities. The system produces customized reporting formats addressing different information needs and decision-making authorities while maintaining scientific accuracy and regulatory compliance.

Scenario 3: Long-Term Mine Water Management Assessment

The third scenario implements the Hydrological Disturbances → Gas Emissions interaction pathway, testing sDSS capability for long-term hazard evolution assessment and adaptive management strategy development. This scenario addresses the complex challenges of mine closure transition and validates system performance for extended temporal analysis applications.

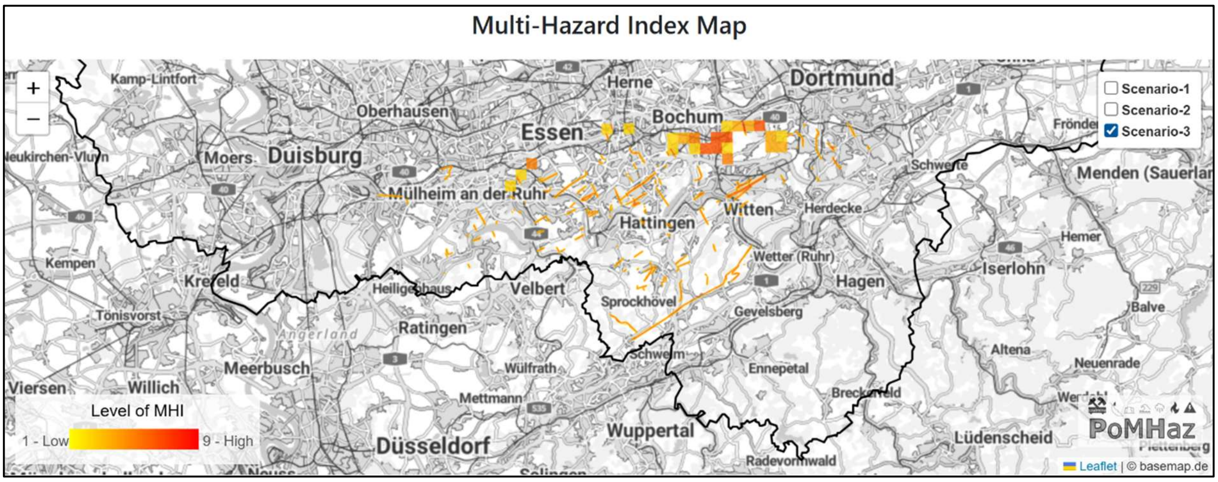

Figure 31: The sDSS Multi-Hazard Index Map for the third test scenario

Application testing validates sDSS capability to address multi-temporal coordination challenges where mine water rebound effects and dewatering adits extend across municipal boundaries. The system supports information sharing protocols, coordinated planning processes, and joint decision-making frameworks required for effective regional post-mining management.

The three-scenario application process demonstrates comprehensive sDSS functionality across the full spectrum of post-mining multi-hazard challenges identified through the stakeholder consultation and expert analysis. System performance validation confirms operational capability to support different decision-making contexts while maintaining consistency with the POMHAZ methodology and integration with broader post-mining management frameworks.

An interactive, multi-purpose dashboard shows the results of the scenarios and can analyze them in the GIS with additional data, e.g. building footprints (Figure 32). Additionally, an automatic report is created (Annex 1).

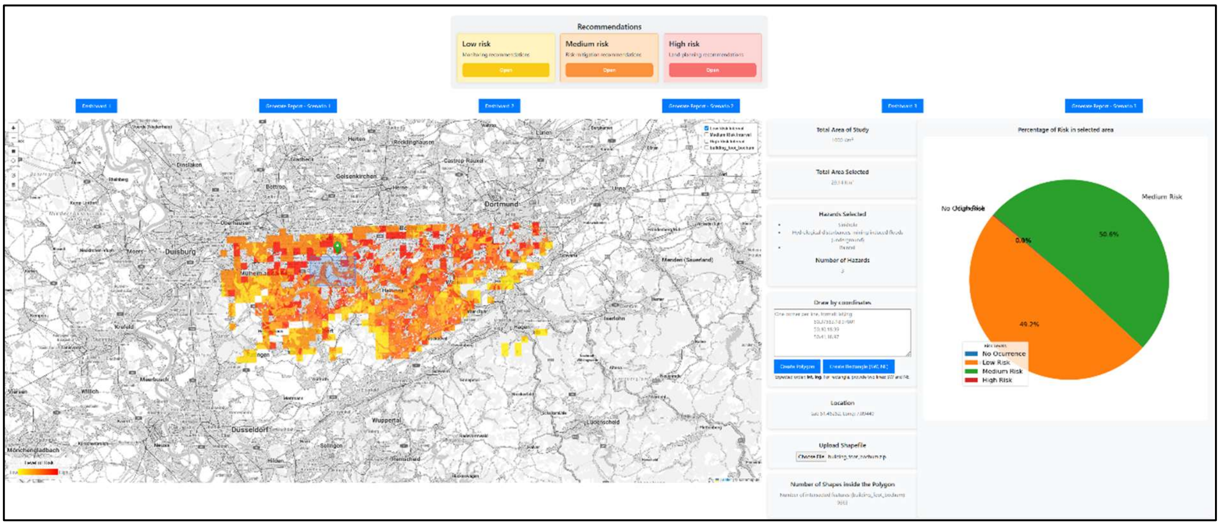

Figure 32: Interactive dashboard showing the different scenario results for further analysis

Results from the southern Ruhr area application provide validation for sDSS deployment in comparable European post-mining regions while demonstrating the practical utility of the multi-hazard assessment approach developed within the POMHAZ project. The successful integration of stakeholder priorities, expert knowledge, and technical capabilities confirms the system's readiness for operational deployment in real-world post-mining risk management applications.

7.2 Megalopolis lignite mine in Greece

To demonstrate the application of the Megalopolis case study in the GIS and DSS interface developed in WP4, two multi-hazard scenarios were constructed based on the outcomes of hazard identification and the susceptibility of the area to rainfall-induced landslides. These scenarios follow the multi-hazard risk assessment framework established in WP3 and integrate the hazard interactions defined through the interaction matrix.

The first scenario represents a cascading sequence where rainfall triggers flooding, and flooding subsequently triggers a landslide. The second scenario reflects an alternative cascade, where an earthquake triggers a landslide, and the landslide in turn trigger flooding. The structure and interaction levels of both scenarios are illustrated in Figure 33.

The scenarios were implemented in the spatial Decision Support System (sDSS) interface, enabling the calculation of the Multi-Hazard Index (MHI) and the visualization of results as spatial maps. The resulting MHI maps for both scenarios are presented in Figure 34 and Figure 35.

Analysis of the maps reveals distinct patterns. As expected, Scenario 1 produces higher MHI values, distributed over a wider spatial area, since rainfall and flood events have a broader impact footprint and stronger triggering potential for slope instabilities. In contrast, Scenario 2 generates lower MHI values, concentrated in smaller areas, consistent with the localized effects of earthquake-induced landslides.

Another important observation concerns the distribution of MHI values in relation to exposed elements. In both scenarios, the highest MHI values are concentrated close to the post-mining areas and in the surroundings of the city of Megalopolis, where infrastructure, buildings, and population clusters increase vulnerability. This demonstrates how hazard interactions, when combined with spatial data on exposure, provide valuable insights into the multi-hazard risk conditions of post-mining regions.

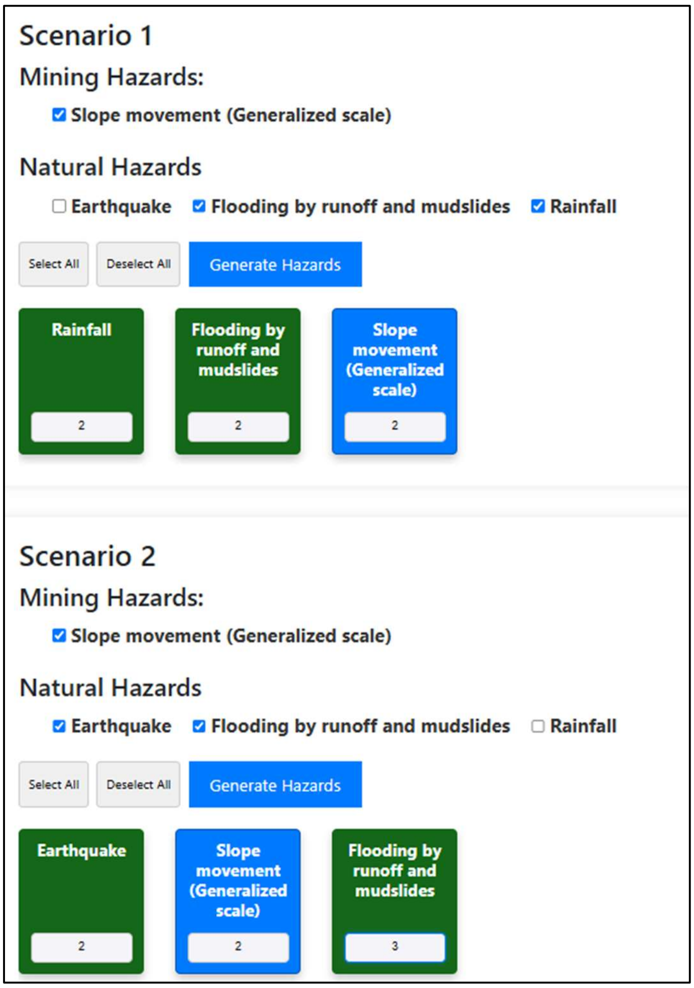

Figure 33: The two Megalopolis post-mining area's multi-hazard scenarios for testing the sDSS capabilities

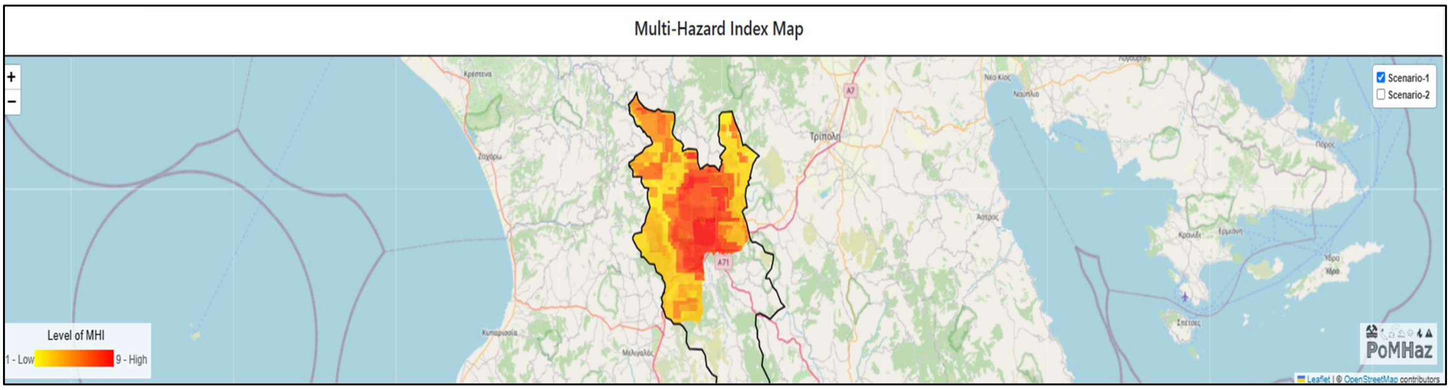

Figure 34: The sDSS Multi-Hazard Index Map for the first test scenario

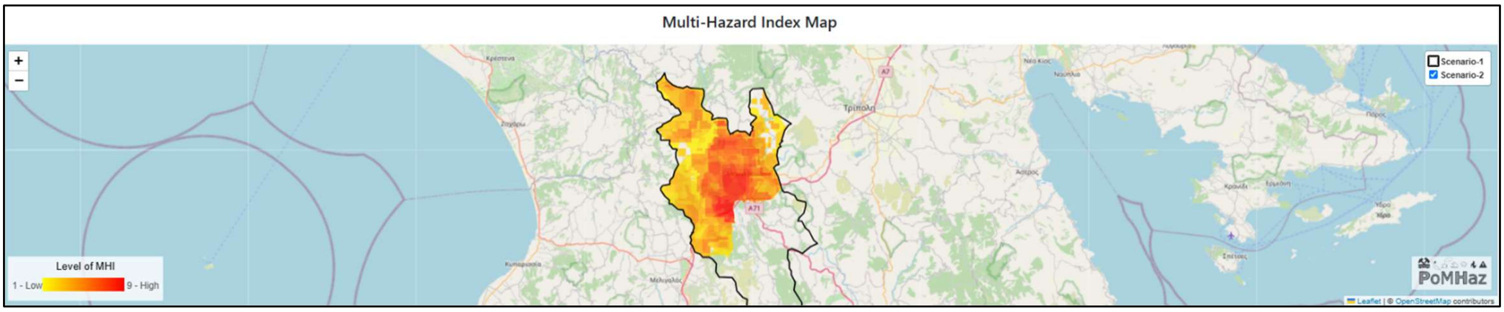

Figure 35: The sDSS Multi-Hazard Index Map for the second test scenario

8 Conclusion

The comprehensive application of the POMHAZ Spatial Decision Support System (sDSS) to the case study of the southern Ruhr area and Megalopolis lignite mine has successfully demonstrated the operational capability and practical utility of the multi-hazard assessment methodology developed within the project framework. This study is a significant step forward in post-mining risk management, offering methodological innovations and practical tools for tackling complex multi-hazard scenarios in densely populated former mining regions.

The development and validation of the hazard interaction matrix is a key contribution to post-mining risk assessment. A systematic analysis for the Ruhr area revealed that 85.5% of the identified hazards are interconnected, which is a significantly higher rate than that typically observed for natural hazards and confirms the complexity of post-mining environments. The matrix-based approach, which incorporates the methodology developed in the POMHAZ project and regional stakeholder expertise, provides a robust framework for quantifying hazard interactions and calculating Multi-Hazard Index values across diverse scenarios.

Integrating comprehensive stakeholder consultation for the German case study with 35 regional experts who self-assessed their knowledge as an average of 80% ensured that the assessment methodology addressed real-world priorities and concerns. Identifying sinkholes as the highest-priority hazard (91/100 points), followed by flooding/precipitation events and environmental contamination (both 80/100), influenced the development of scenarios and the priorities for system testing.

The sDSS successfully integrated heterogeneous datasets, including geological information, historical mining records, infrastructure databases and demographic data, within operationally relevant timeframes. Its ability to process risk assessments within minutes of scenario activation confirms the system's suitability for emergency response applications, all the while maintaining scientific rigour and regulatory compliance.

The three-scenario testing approach for the Ruhr area validated sDSS performance across different temporal scales and decision-making contexts:

- Scenario 1 confirmed rapid-onset hazard assessment capabilities for precipitation-triggered events
- Scenario 2 demonstrated environmental contamination pathway assessment for long-term impact evaluation
- Scenario 3 validated long-term mine water management assessment for adaptive planning applications

The case study of the southern Ruhr area provided valuable insights into the complex legacy of mining operations that have been ongoing for centuries in densely populated urban environments. In North Rhine-Westphalia (NRW), there are approximately 31,000 documented abandoned mine openings, extensive dewatering systems and ongoing mine water rebound processes, which create multi-layered hazard conditions requiring sophisticated assessment approaches. The analysis revealed critical vulnerability patterns where high-density urban development overlies complex post-mining substrates. This creates infrastructure risks that differ significantly from those in rural post-mining areas. Successful mapping across 22 municipalities demonstrated the system's capability to support regional-scale land use planning and infrastructure protection decisions.

In addition to the Ruhr area, the application of the multi-hazard risk assessment framework in the Megalopolis lignite basin in Greece demonstrated its adaptability to regions with different geological and socio-economic conditions. The case study highlighted the susceptibility of post-mining slopes to rainfall-induced landslides and the significance of cascading hazard interactions, particularly between rainfall, flooding, and slope instability. By constructing two scenarios - one linking rainfall, flooding, and landslides, and another linking earthquakes, landslides, and flooding - the framework illustrated the spatial distribution of multi-hazard risk. The resulting MHI maps confirmed that rainfall-triggered cascades generate higher values and wider affected areas compared to earthquake-triggered scenarios. Furthermore, the analysis emphasized that the highest MHI values occur near the post-mining sites and around the city of Megalopolis, where exposed elements such as infrastructure and settlements are concentrated. These findings validate the framework's capacity to identify critical hazard interactions and provide decision support for both environmental reclamation and urban safety in post-mining landscapes.

The POMHAZ sDSS is a significant technological advancement in post-mining risk management. It combines established scientific principles with modern GIS technology and AI-assisted analysis to generate customised risk communication materials for diverse stakeholder audiences. It also maintains scientific accuracy and addresses critical multi-jurisdictional coordination challenges. The validated interaction matrix methodology provides a transferable framework for post-mining regions across Europe and beyond, successfully integrating mining legacy data, natural hazard assessment and infrastructure vulnerability to create a comprehensive approach that addresses the full spectrum of post-mining challenges.

The result of the validation has been successfully achieved in the contexts of emergency response, environmental management and long-term planning, demonstrating the system's comprehensive functionality and readiness for practical implementation. The system's integration with existing data sources and compatibility with standard GIS platforms ensures feasibility of implementation within established institutional frameworks. The flexible framework also accommodates diverse geological conditions, mining legacies and socioeconomic contexts across European post-mining regions. This case study shows that sophisticated, multi-hazard assessment approaches can be successfully implemented in complex, real-world environments. They provide essential tools for managing ongoing post-mining challenges and support sustainable development objectives by enabling evidence-based decision-making that considers stakeholder priorities, expert knowledge and technical capabilities. The case studies confirm that the sDSS is ready for operational deployment. However additional effort should be carried out to compare the multi-hazard analysis with traditional single hazard analysis in real-world applications, before reaching the policy level at European scale for Coal Regions in Transition.

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10 Annexes

List of annexes:

- Annex 1: Automatic report of the DSS simulation

Annex 1: Automatic report of the DSS simulation

Post-Mining Multi-Hazards evaluation for land-planning

Report of the DSS simulation

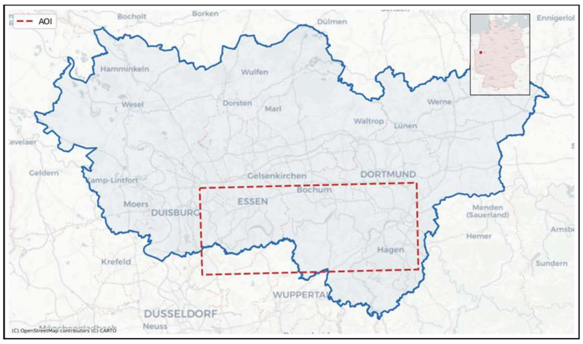
Operator: Public User	**Case Name: Pomhaz DSS study cases**	**Date: 2025-09-29**

General Description:

The Ruhr area (Germany) was the most dominant coal mining region in Germany. The entire Ruhr area covers more than 4,000 km² and more than 5 million inhabitants live in this region. In order to dewater the overlying strata and coal seams, the miners erected dewatering adits and tunnels into the slopes of the adjacent hills. More than 100 of these tunnels exist, and some are still dewatering even today. These old galleries are sometimes several kilometers long and spread over a larger area. However, their length and spatial extent are in many cases not entirely known, and maps or other information do not exist or are only partial.

Water from these galleries can contain sulfide, iron, and other chemicals and flows into the small streams and finally into the river Ruhr, polluting the river water. These galleries also pose another risk to the inhabitants and infrastructure of that area because they can be unstable and prone to collapse. This happened, for instance, in 2017 when the "Franziska Erbstollen" near Witten collapsed close to a person's home and destroyed the road. Until today, there exists no monitoring and risk management tool for this type of coal mine legacy.

Area of Interest (AOI):



Hazards:

• Flooding by runoff and mudslides
  Description: Pluvial/flash flooding and associated mass flows caused by intense rainfall that overwhelms infiltration and drainage, producing rapid overland flow and, on steep slopes, debris-rich flows.
  Effects: Rapid onset with little warning; localized but destructive flooding and debris impacts on buildings, culverts and roads; high sediment loads and blockage of drainage.

• Hydrological disturbances, mining induced floods (underground)
  Description: A common practice to form a pit lake is by flooding the remaining voids after the mine closure. These voids can be filled
by artificially flooding or allowing the pits to fill naturally through hydrological and hydrogeological processes such as precipitation or ground water infiltration and inflow.(Burda, J., & Bajcar, A. (2020). Post Exploitation Lakes. Zpravodaj Hnědé uhlí, Most.). Liquidation of opencast workings may also take place by prior partial leveling of the area with the use of post-mining waste and then creating a water reservoir, or by completely filling the open pit with post-mining waste, and then by liquidating the mine drainage system. The flooding of an open pit reclaimed in this way occurs as a result of free recharge with groundwater (lateral and ascending tributaries) and surface water (from watercourses) and atmospheric water (precipitation).
  Effects: Floods into the pit lake. Pit flooding generally induces groundwater rebound with short and long time consequences, such as soil instabilities causing landslides and subsidence (Burda,

J., & Bajcar, A. (2020). Post Exploitation Lakes. Zpravodaj Hnědé uhlí, Most.). Reconstruction of the groundwater table as a result of the sinking of the open pit carries the possibility of ingression of contaminated water in the open pit into the groundwater in its vicinity. On the other hand, the open-pits closure by filling them with post-mining waste and the cessation of mine drainage may cause damming of underground waters and the formation of floodplains on the surface. These hazards may limit the possibilities for development of open pit and adjacent areas.

• Gas emissions linked to mining

Description: In case of closed down mines, after damming up water to a safe leve (in order to protect neighboring active mines against water hazards) the phenomenon of pushing out of mine gases in some areas is oberved. The presence of water and hydrostatic pressure in flooded mines limits the desorption and migration of methane from the unexploited seams destressed by mining. As a consequence of the water table rising as a result of mine flooding, the following phenomena occur:

• a drop in the intensity of methane desorption resulting

from the effect of increased hydrostatic pressure and filling gas migration with water (residual voids, pores, fissures)

• increase of free gas pressure in the workings over the water level,

Effects: The damming of groundwater during the flooding of mines can cause the migration of mine gases (mainly methane) towards the surface and pose a general threat. Due to hydrogeological disturtances, drainage causes depletion of water resources, strengthening of the rock mass and an increase in the main mining hazards e.g. methan and CO2 emission. Methane is a colorless and odorless gas whose greenhouse potential – the effect it has on the greenhouse effect – is 28 times stronger than that of carbon dioxide (over a hundred years). Moreover in the case of flooding mines, water gradually pushes methane to the surface, which may accumulate, for example, in basements. Penetration of methane to the lower storeys of buildings, garages, as well as telecommunications and sewage channels may cause an explosion hazard at concentrations above 5%, while carbon dioxide may pose a threat to the health and life of residents.

• Environmental pollution from spoils

Description: The wastes have been excavated and placed on the surface of the earth. Spoil material is conducted from i.a. heavy metals and sulfide minerals. Natural weathering conditions influence spoil material and cause its breakdown. Then, the fine material can be easily released into the environment

Effects: The appearance of spoil material into the environment in combination with the weathering, speed up the release of toxic elements and conservative pollutants (Dang, Z., Liu, C., & Haigh, M. J., 2002). Changes in hydrogeological conditions in the area of the flooding mine may significantly affect the groundwater vulnerability to pollution (including pollution emitted from post-mining waste heaps) Bukowski P., Bromek T., Augustyniak I. 2006 - Using the DRASTIC System to Assess the Vulnerability of Ground Water to Pollution in Mined Areas of the Upper Silesian Coal Basin. Mine Water Environ., 25: 15-22.)

• Rainfall

Description: Precipitation of liquid water drops from clouds; extreme or prolonged rainfall is a primary trigger for secondary hazards.

Effects: Heavy rain can overwhelm drainage systems, trigger floods, landslides and soil erosion; disrupts transport and utilities; increases water-quality and health risks.

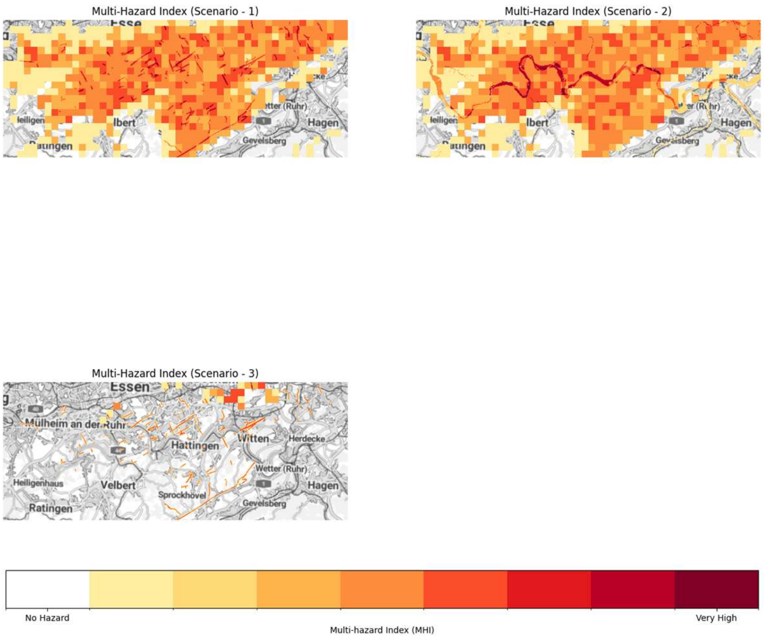
• Sinkhole

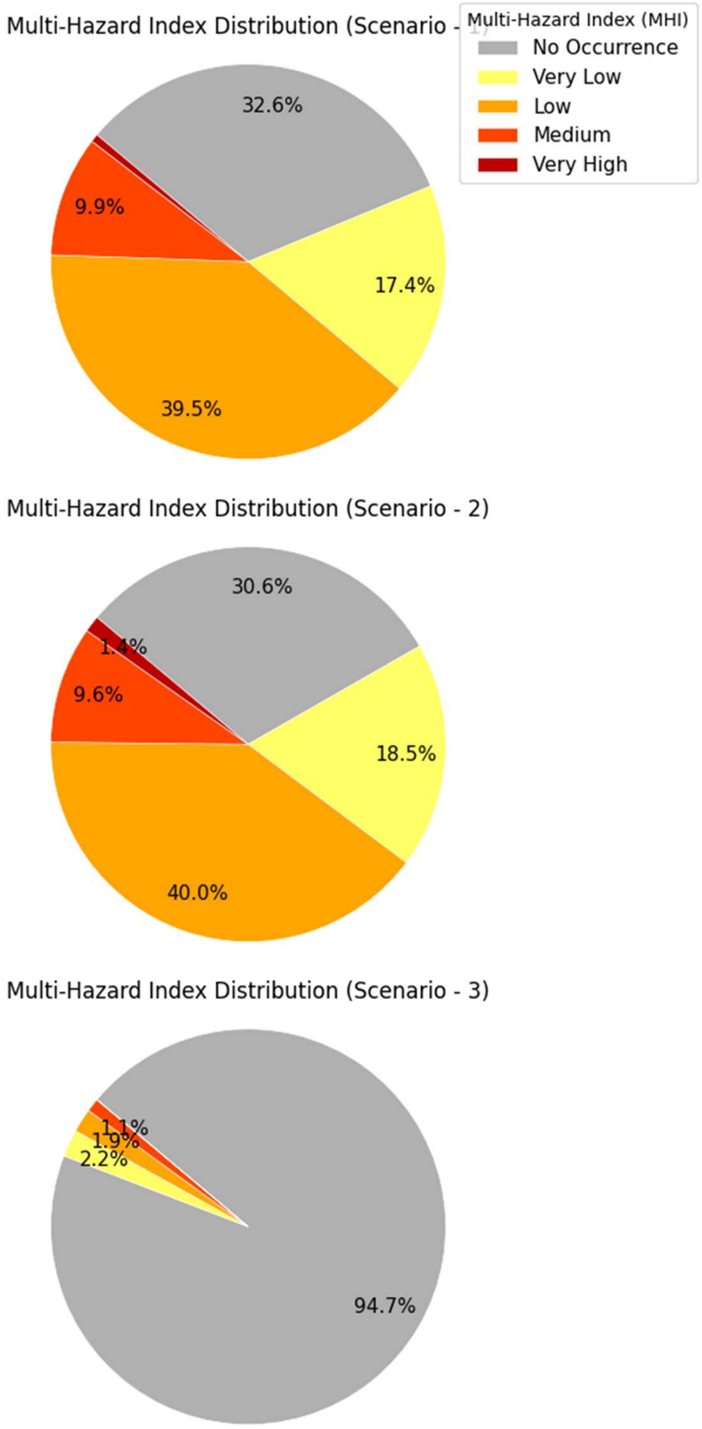
Description: Sinkhole is an abrupt depression of the local ground surface which occurs due to sudden collapse of overburden into a mine opening or cavity (Singh and Dhar, 1997), observed both during mine drainage and during mine closure and flooding. Sinkholes are surface, discontinuous deformations.

Effects: Dangerous to life and property, damage to existing development and infrastructure; and, in the worst cases, injury or loss of life. The economic impact of sinkhole, in the form of loss of surface and underground property, disruption of work, production loss, cleaning of the sinkhole in affected areas and filling of the sinkhole, is also significant in many cases. Temporary or permanent exclusion of the area from use or the need to displace people. Changes in hydrogeological conditions - facilitating water infiltration and migration of contaminants from the surface. Drainage of groundwater levels. The need for costly subsoil investigations and hazard monitoring in conjunction with hydrogeological monitoring. Use of expensive stabilizing mixtures for underplanting.

Results of Assessment

Multi Hazard Index factor results for different scenarios:





Total area evaluated: 1000.00 km².

Multi-Hazard Index map of Scenario 1 evaluates a total of 2 hazard(s):

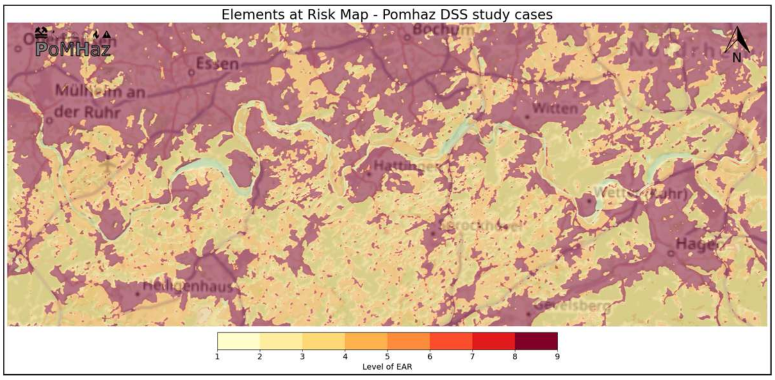
Sinkhole hazard:

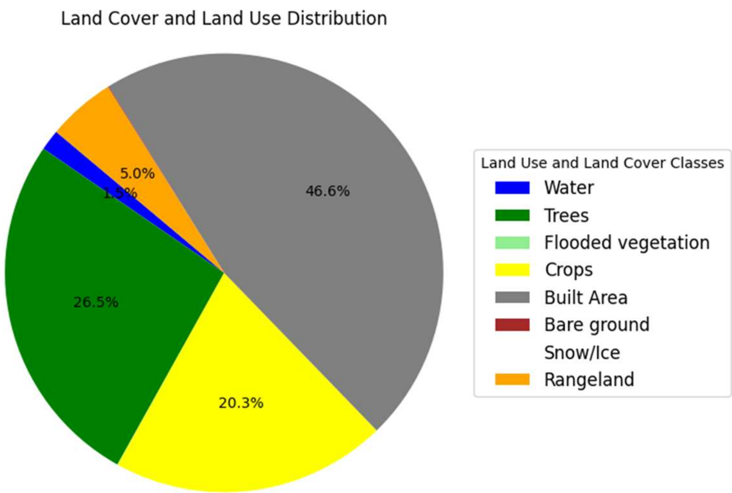
- 17.40% of the AOI has hazard intensity 2 classify as very low.
- 17.10% of the AOI has hazard intensity 3 classify as low.
- 24.10% of the AOI has hazard intensity 4 classify as medium.
- 8.80% of the AOI has hazard intensity 5 classify as high.

Hydrological disturbances, mining induced floods (underground) hazard:

Multi-Hazard Index map of Scenario 1 evaluates a total of 0 hazard raster(s):

Exposed element at Risk factor results:

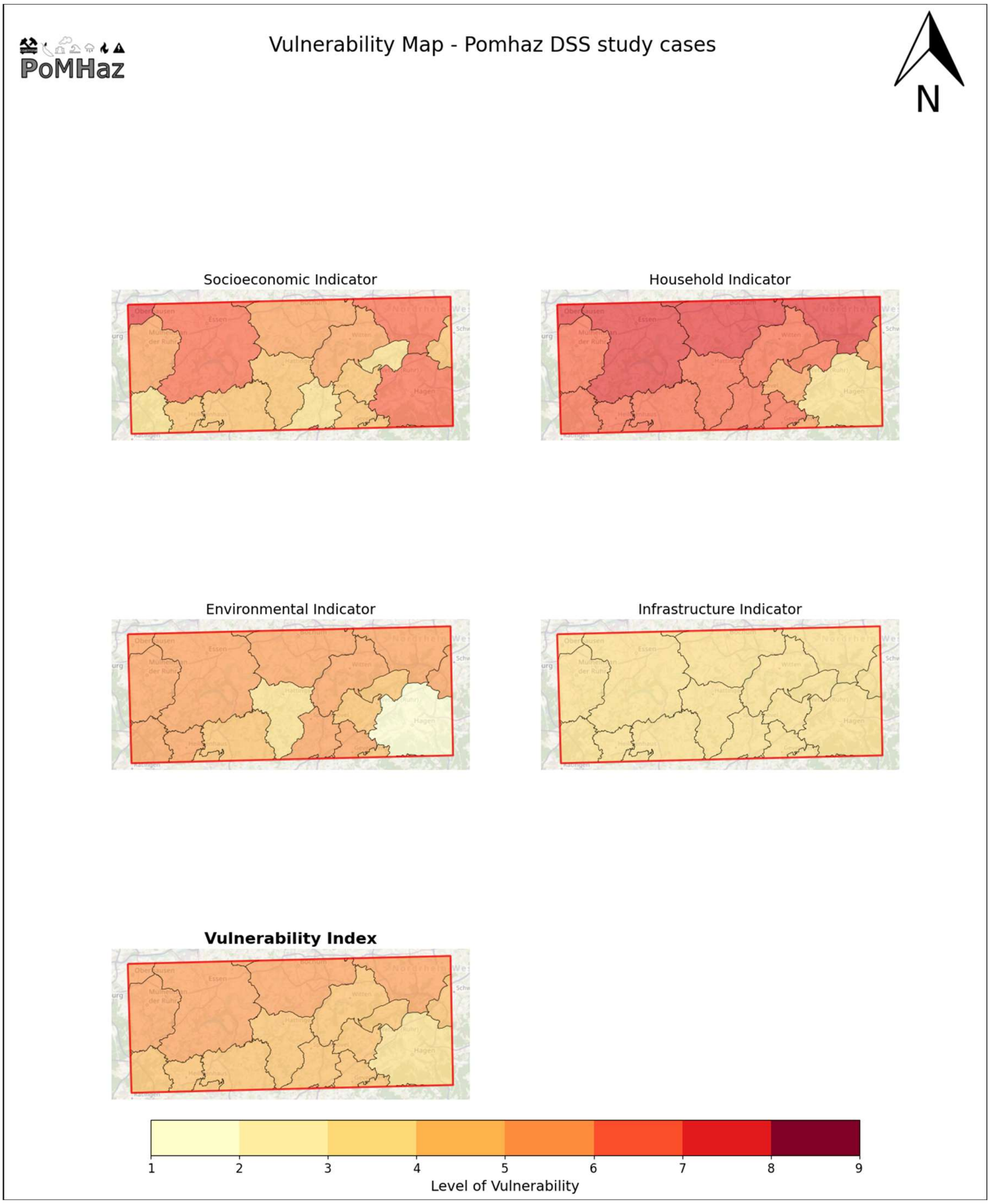




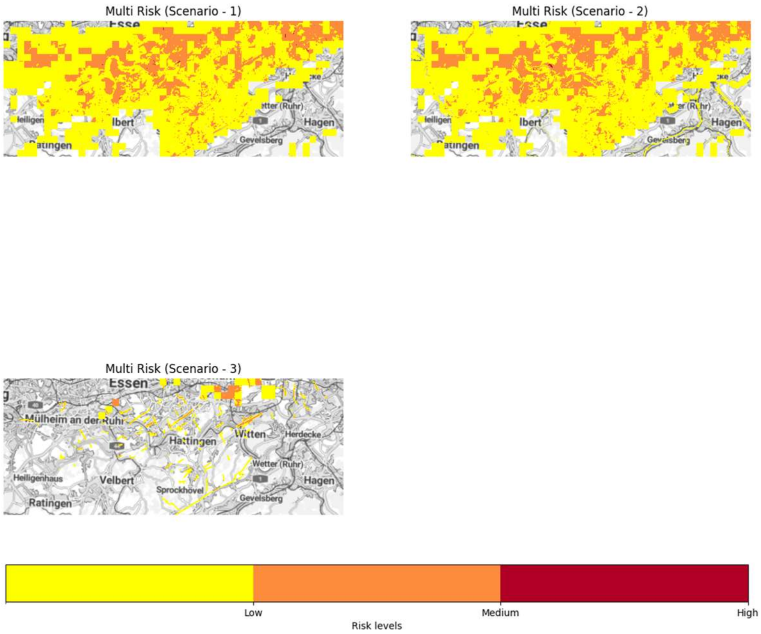
The area evaluated presents the following distribution of Elements at risk:

Very Low: 1.64% Low: 51.77% Medium: 0.00% High: 0.00% Very High: 46.59%

Vulnerability factor results:



Multi Risk results:



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.

The PoMHaz Consortium

ΔEH Public Power Corporation

INERIS maîtriser le risque pour un développement durable

Technische Hochschule Georg Agricola

GIG National Research Institute

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