Post-Mining Multi-Hazards evaluation for land-planning

PoMHaz

WP4: GIS development tools

D15: Deliverable D4.4: Coupled GIS-DSS module with an intuitive interface and guide document, documented in a verification case

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Acronyms

RFCS	Research Fund for Coal and Steel
GIS	Geographic Information System
DSS	Decision Support System
GIG-PIB	Główny Instytut Górnictwa – Państwowy Instytut Badawczy (Central Mining Institute – National Research Institute)
THGA	Technische Hochschule Georg Agricola
GZW	Górnośląskie Zagłębie Węglowe (Upper Silesian Coal Basin)
GSIS	Górnośląska Skala Intensywności Sejsmicznej (Intensity Scale of Mining Seismic Evenets)
MHI	Multihazard Index
VI	Vulnerability Index
GDP	Gross Domestic Product
AOI	Area of Interest

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 transition.

In the POMHAZ project, the present deliverable is part of the WP4 that is dedicated to GIS development tools. This WP's goal is to develop the post-mining risk information system that supports planning and decision making and provides interpreted information to stakeholders. This deliverable is related to Task 4.4 "System verification".

It was assumed that the developed post-mining risk information system, using the GIS and DSS will be tested and verified on fully known historical case. For mining application, related to Polish hard coal mines, the following cases/cities were chosen: Sosnowiec, Piekary Śląskie and Wałbrzych.

The first two cities are located in southern Poland in the Upper Silesian Coal Basin. Wałbrzych is located in the western part of the country. The cities have a long history of mining of mineral resources. However, in each of the cities, there are significant differences related to different geological conditions In Piekary Śląskie, zinc and lead ores, lying above the coal seams, were mined for several centuries, resulting in the overlapping effects of shallow and deep mining. As a result, the geological environment in Piekary Śląskie is more transformed and disintegrated than in other analysed cities. A very important factor that differentiates the selected locations is the time when the mines were completely liquidated. Coal mines in Sosnowiec had been in operation since the 19th century. Last one was closed in 2021. In Piekary Śląskie mining activity has been carried out for more than 800 years - the effects of historical shallow exploitation of metal ores and deep coal mining are overlapping. The last coal mine was closed down in 2020. The last ton of hard coal within the borders of Wałbrzych and its surroundings was exploited in 1998.

To achieve the goal of Task 4.4., it was necessary to create a database of available data determining hazards in selected cities in mining areas. GIG-PIB was responsible for collecting data and creating databases, according to the deliverable D3.3"DSS tool and report detailing its application" related to Task 3.3 "Development of a DSS for Risk management" and common agreements with the partner THGA.

This document presents the stages of work leading to the realization of the goal, which is the verification of the system developed by THGA that supports planning and decision making. The stages of work are presented according to the work schedule.

In the first chapter, the selected case studies for testing are briefly introduced. The chapter 2 provides the description of the coal mine, including geology and mining methods. One subsection is dedicated to the topography of the individual cities, because it has a direct impact on hazards and risks. An important factor shaping the development of hazards is the described history of exploitation – past mining methods, methods of mine closure, and the time that has passed since the closure of the mining facilities. The document also describes actions that have been taken systematically, regulated by legal regulations or recommended instructions, aimed at monitoring adverse phenomena.

In order to achieve the assumed goal, it was important to be aware of the significance of hazards, their mutual interactions. A ranking of the significance of individual hazards in each city was presented at the initial stage of the project, as well as its verification. Changes were made based on the detailed data obtained and the results of research conducted in the cities. This stage of work was concluded with the presentation of the matrix that illustrates the results of the interaction analysis conducted for the Upper Silesia region (Poland). The analysis takes into account specific local geological and technical conditions. A logical next step was to create the interaction between hazards, and calculation of the multi-hazard index. Hazards in mining areas often cause damage to buildings and infrastructure crucial for its functioning. The cities for which the hazard analysis and verification of the GIS DSS system were carried out are relatively densely populated, covered with a network of roads, and have infrastructure (energy, gas, and other) vulnerable to the effects of centuries-old mining activity.

The vulnerability assessment of each area depends on many specific factors. The factors were divided into groups: socioeconomic status, household composition, environment, infrastructure. Information and data were collected for each city, which served as the basis for calculating the so-called Vulnerability Index.

The most important element of the work performed was the verification of the decision support system tool (DSS). The evaluation of the system and the maps of hazards and multi-multihazards were carried out for 3 post-mining cities. For this purpose, the team that developed the GIS DSS tool (THGA) used databases detailed for real conditions of well recognized case studies, delivered by GIG-PIB.

The next step is the presentation of GIS and DSS in real case studies, discussion of the results within the frame of workshops with stakeholders such as local administrations, representatives of the association of mining municipalities, the State Mining Authority and experts. The discussion and presentation of the results with/to end-users will be very important for applying the developed tools.

1 Background

1.1 Description of the WP4

Deliverable D4.4., entitled “Coupled GIS-DSS module with an intuitive interface and guide document”, refers to WP 4 GIS development tools.

The overall goal of WP4 is the development of a Post-Mining Risk Information System that supports planning and decision-making and provides interpreted information to stakeholders. Reaching this goal involves the achievement of following objectives:

- To develop the system architecture, data structure, analysis engines and a user front end of a GIS- solution tailored to post mining risk assessment;
- To implement the concept for selected case studies;
- To verify the functionality for a selected case study.

The work package has 4 tasks:

- Task 4.1. Requirement analysis for and design of a Post-Mining Risk Information System architecture
- Task 4.2. Implementation of interfaces and database system
- Task 4.3. GIS and DSS Development and Advanced data visualization
- Task 4.4. System verification.

This deliverable (D4.4) concerns the Task 4.4.

1.2 Description of the T4.4

For a mining application related to Polish hard coal mining, the developed post-mining risk information system using the GIS and DSS will be tested and verified on a fully known historical case related to WP5 (Task 5.2). The database will be provided by GIG-PIB. As a result of the tests, the overall system performance and the results of the decision support system will be evaluated, and Hazard maps will be provided. CERTH and TU BAF will work together to consider the shortcoming observed and identified from the trial tests.

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

In Poland 3 investigation coal mining sites were chosen: Sosnowiec, Piekary Śląskie and Wałbrzych. The location of Polish sites is presented below, Figure 1.

Figure 1 - The location of case study in Poland

Sosnowiec

Sosnowiec is one of the central hubs of the Upper Silesian conurbation, located in the southern part of Poland, on the Silesian Upland, which is part of the Silesian-Cracow Upland, in the central area of the Upper Silesian Industrial District. The city covers an area of approximately 91 km². Coal mines had been operating since the 19th century, with the last one being closed in 2021. Part of the post-mining area of the city has been transformed into industrial and recreational areas (see Figure 2 a,b).


a.

b.

Figure 2 a, b - New residential estate and recreational area on post-mining land in Sosnowiec
https://pl.wikipedia.org/wiki/Sosnowiec

Piekary Śląskie

Piekary Śląskie is located in the southern part of Poland, in the Silesian Upland, within the Upper Silesian conurbation. The city lies in the central area of the Upper Silesian Industrial District, part of the Silesian Voivodeship. It is situated close to other major cities in the region, such as Katowice and Sosnowiec. The city is located in the northern part of the Silesian Upland. Currently, no coal mines operate within the city's boundaries, and some of the post-mining areas have been revitalized (Figure 3 a, b).


a.

b.

Figure 3 a, b - New residential estate and post-mining land in Piekary Śląskie
https://upload.wikimedia.org/wikipedia/commons/9/91/009_Osiedle_Wieczorka%2C_Piekary_Slaskie%2C_Poland.jpg,https://upload.wikimedia.org/wikipedia/commons/thumb/3/35/Brynica_rzeka_piekary_slaskie_brzozowice-kamien.jpg/1024px-Brynica_rzeka_piekary_slaskie_brzozowice-kamien.jpg

Wałbrzych

Wałbrzych, the most important city of the Walbrzych Basin, is situated in the south-western part of Poland (Figure 1). It is surrounded to the north by the Wałbrzyskie Mountains with part of the Trójgarb Massif and the Chełmiec Massif. The mining area of the Wałbrzych region, with an area of 94 km^2, is located in the mid-mountain depressions of the Central Sudety Mountains. Walbrzych, with its extensive mining infrastructure, is undoubtedly a testimony to the process of industrialisation that took place in the 19th and 20th centuries in Europe, and the architectural and technical qualities of some of the buildings are worthy of preservation (Figure 4 a, b).


a.


b.

Figure 4 a, b - Wałbrzych, Magistrate Square at night, viewed from the Municipal Park
https://pl.wikipedia.org/wiki/Plik:PL_Walbrzych_Widok.JPG

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

3.1 Geology and Hydrology

3.1.1 Sosnowiec

Geological information

Sosnowiec is located in the north-eastern part of the GZW. The crystalline bedrock of the area (located within the Western European platform) is composed of crystalline (magmatic and metamorphic) rocks of the Precambrian, on which younger formations, representing the cover floor of the platform, unconformably depend (Cabała, Żaba, 2016).

The rocks underlying the GZW in the Sosnowiec area are represented by Precambrian, Cambrian, Devonian and Lower Carboniferous formations. On the foliated Palaeozoic formations in the area of the city, Mesozoic (thickness up to 120 m) and Cenozoic (thickness up to 60 m) formations lie unconformably. The Mesozoic formations include Triassic sediments, developed in carbonate and sandy-siltstone facies, occurring within the extent of the Bytomian Basin. The thickness of the Triassic is variable, depending on the tectonics of Cenozoic erosional processes (Kotlicki, 1962, Jureczka, Kotas 1995). The Cenozoic formations (thickness up to 60 m) include Quaternary sediments developed in the form of variously grained sands and glacial till, filling up the valleys of the older bedrock (Wagner et al. 2009).

Lithology and stratygraphy

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

Quaternary - thickness, lithological structure.

Sediments of this age were formed during the South and Central Polish glaciation and the Holocene. They are highly variable both vertically and horizontally. The greatest thickness of Quaternary formations (up to 80 m) is observed in river valleys. They are represented by variously grained sands, silts and river silts. The Pleistocene is developed as fluvioglacial deposits, sands, gravels and glacial till. These sediments have been deposited on the erosional surface of the bedrock. They lie unconformably on Triassic formations and locally (erosional window zones) directly on Carboniferous. They are formed in the form of poorly failing medium-grained sands, yellow-grey clays and sandy loams. The clays are residual in character. Locally they are mixed with weathered Triassic formations. In the lowest parts of the profile of the Quaternary formations, there are insets of impermeable clayey formations. The youngest are Holocene sediments occurring within river valleys. In the valley of the Czarna Przemsza River, Holocene sediments several metres thick are composed of variously grained sands, silts and river muds. Anthropogenic slag and shale-sand mounds can also be included in Holocene formations.

Quaternary sand and gravel formations are of great economic importance. They are exploited for construction purposes and as filler sands for coal mines.

Triassic

Triassic sediments lie unconformably directly on top of the Carboniferous. They form irregular covers often preserved in the form of erosional patches from 0 to 150 m thick. Only Lower and Middle Triassic formations are represented in the Sosnowiec area. The Lower Triassic (the Brackish Sandstone) is developed in the form of weakly compacted sandstones, fine- and medium-grained sands, grey and cherty siltstones, among which green-grey cratered siltstones, cherty hard and plastic siltstones are the most common. The Ret (Upper Sharp Sandstone) is developed as marls and dolomitic limestones. Locally in the lower Triassic, limestone and dolomite crumbles occur among the sands and clayey formations, indicating erosion and displacement of material from the higher, carbonate parts of the Triassic profile. The Middle Triassic (shell limestone) is built up by limestone, marls and dolomites. Dolomitised Triassic limestones in the Sosnowiec area have been exploited in several small quarries.

Carboniferous

Upper Carboniferous formations are represented by sediments of the paralic Namurian A and limnic series corresponding to Namurian B-C and Westphalian A and B. The Upper Carboniferous sediments are composed of sandstones, siltstones, mudstones, shales and conglomerates, within which there are insets and coal seams. In the formations of the Paraltic Carboniferous series in the Sosnowiec area there are also clay raw materials (montmorillonite), the most important of which are bentonites. One of the largest deposits of bentonite and bentonite clay has been documented in the mining area of KWK ‘Milowice’, and the occurrence of bentonite rocks has also been found in the ‘Sosnowiec’ mine. A characteristic feature of the geology of the area, favourable for the development of mining, is the shallow occurrence of Upper Carboniferous formations with coal seams having numerous outcrops on the surface. In addition, the coal seams are characterised by their considerable thickness, good quality (high heating value) and relatively low methane content.

Deposit series (strata)

Orzeskie layers: siltstone and claystone with coal seams, thickness up to 260m.
Rudzkie strata: siltstone, hard medium- to fine-grained siliceous sandstone with thin coal seams, thickness of the complex 160-230m.
Saddle layers, with seams of coal 501 and 510, with thicknesses locally reaching up to 20 metres. Thickness of seams (500-settings) of coal in the saddle layers: up to 17 metres. For many years, the coal from the 510 seam was the main resource of the mines operating in the town. The coal seams are interlayered with clay shales and sandstones. The total thickness of the deposit is approximately 50 metres.
Porębskie layers - composed of clay rocks with thin coal seams at the balance limit (i.e. 0.8m). Thickness of the complex up to 290m.
The Devonian is represented by grey limestones overlain by marls, and dolomites containing intrusions and laminae of anhydrite.
Cambrian represented by sandstones, siltstones and subordinate conglomerates.
Precambrian formations in the Sosnowiec area have not yet been identified. They lie below the range of the deepest drilling in the area. Probably these rocks are present here only at the depth of 5 or even 5.5 km below the ground surface (Buła, Jachowicz, 1996, Cabała, Żaba, 2016).

Tectonics

Sosnowiec is located in the area of the unit known as the Sosnowiec dome, which is part of the large structure that is the Main Saddle.

The tectonics of the area is complex, with numerous continuous and discontinuous deformations. There is a system of faults, often with significant throws. For this reason, the course of the strata sometimes changes significantly, e.g. from NNE-SSW to NW-SE and then to almost parallel. In different parts of the mining areas, the strata dip at an angle of 15-350, then lie almost horizontally.

Hydrology

The city of Sosnowiec is located in the basin of the Przemsza River, which is the main river of the city. The Przemsza belongs to the catchment area of the Vistula River (Poland's largest river) and is its left-bank tributary. In addition to the Przemsza, Sosnowiec is drained by tributaries of this river, which include the Brynica, Potok Zagórski and the Biała Przemsza. In addition, within the city, the White Przemsza is fed by the Bobrek river and its tributaries - the Jamki stream and the Dańdówka stream. The beds of all rivers and streams are fully or partially regulated and embanked. The hydrographic network of Sosnowiec is supplemented by anthropogenic watercourses, ditches and canals whose main function is drainage and the discharge of treated sewage from the city area. The most important are the Mortimerowski Canal (**Figure 5**), and the Klimontowski Ditch, whose receiver is the Bobrek River. The Mortimerowski Canal originally discharged pit water from the Central Mine Dehydration Plant, now it discharges rainwater from the city and treated wastewater from the 'Zagórze' wastewater treatment plant. The Klimontowski ditch, on the other hand, drains rainwater from the urban areas of the Klimontów district.

Figure 5 - Montimerski Canal
https://www.geocaching.com/geocache/GC9A2Q2, 06.03.2025

There are 3 large surface water reservoirs within the city limits:

- Balaton - with an area of approx. 10 ha,
- Stawiki - with an area of approx. 8 ha,
- Leśna Reservoir with an area of approx. 5 ha.

In addition, smaller, individual water reservoirs as well as lagoons are found throughout Sosnowiec. All water reservoirs have an important ecological function. The largest reservoirs are used for recreation by the town's residents.

3.1.2 Piekary Śląskie

Geological information

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

Quaternary: represented by Holocene and Pleistocene deposits, sometimes reduced or with a thickness not exceeding a few meters. The thickness of the Quaternary sediments varies greatly, locally reaching 40m but averaging a few metres. The thin Quaternary layer covering the Middle

Triassic dolomites do not have an isolating character, as these are generally semi-permeable and permeable deposits, formed as, for example, clayey weathered materials (Kotyrba, 2001).

Tertiary: remnants of Tertiary marine deposits are represented by patches of clayey-sandy formations up to about 40 meters thick. The Tertiary is observed in the Bytom Basin mainly by traces of strong erosion, reaching the level of Gogolin layers and the bottom parts of ore-bearing dolomite.

Triassic: beneath the thin layer of Quaternary deposits lies a complex of Triassic formations, with a thickness reaching up to 160 meters. The layers are represented by marly dolomites, massive, only slightly porous, laminated spongy and cavernous ones with numerous voids. Another carbonate rocks of Triassic are ore-bearing dolimites: fine-grained, generally hard and compacted, very often weathered, which promotes the development of karstification. The ore-bearing deposits, up to 4 meters thick, were mined until 1989. The next layers of Triassic sediments are limestone, marl, often fractured. The physical properties of the carbonate series facilitate the migration of water and gases.

Carboniferous: directly below the Triassic formations. Carboniferous developed in the form of alternating layers of siltstone, mudstone, sandstone and coal seams. Coal seams belong to the Ruda, Saddle and Porębskie strata. Productive Carboniferous deposits were accessible up to a depth of about 600 meters.

Tectonics

The tectonics of Piekary Śląskie are characterized by the complex structure of the Silesian-Cracow Monocline, which forms part of the Upper Silesian Coal Basin. The region has been shaped by various tectonic processes, including compression and folding, resulting in the formation of anticlinal and synclinal structures. The area is primarily influenced by the activity of fault systems, which have led to the development of significant geological discontinuities. These tectonic forces have contributed to the deposition of various sedimentary layers, including Triassic, Jurassic, and Tertiary formations, as well as the presence of mineral deposits, particularly coal and ores.

Hydrology

The hydrology of Piekary Śląskie is influenced by the region's location in the Upper Silesian Basin, with a network of rivers and streams draining the area. The main watercourse is the Brynica River, which flows through the city. Groundwater in the region is primarily contained in sedimentary aquifers, with varying depths depending on local geological conditions. The local water resources are mainly used for industrial, municipal, and agricultural purposes. Additionally, the region faces challenges related to the management of water quality and the effects of mining activities on local water systems.

3.1.3 Wałbrzych

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

Characteristics of lithostratigraphic layers

Anthropogen: industrial heaps - waste rock (clay shales, siltstones and sandstones, some coal fragments are found among them) and ashes, slags, porphyry, melaphyr sands and tailings silt. There were more than 30 heaps within the city boundries. A few are still present in the city landscape.

Holocene - Pleistocene: soil 0.1 to 1.0 m thick; peats, sands and gravels of valley bottoms and river terraces. Fluvial valley dusts and muds, clays, gravels and sands.

Pleistocene: loess, sands, glacial water gravels, glacial till and others.

Neogene: clays and siltstones of the limestone facies. Lignites, sands, gravels.

Cretaceous: siliceous siltstones, calcareous siltstones. Claystone, calcareous sandstone, feldspathic sandstone, quartz. Quartz-barite and barite-calcite veins encountered.

Trias sandstone: greywacke sandstones (thickness 70-110m).

Lower and upper Permian Zechstein (Turing) and Redstone: sparse sandstone outcrops.

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

Lower Carboniferous: Lower Turne - Upper Visayan: massive sandstones with lenticular packets of siltstone and claystone.

Devonian: sandstones, conglomerates and siltstones.

Tectonics

The complex structure of the area is related to intrusive tectonics and Asturian compressional tectonics (Seredyńska-Iwaniuk, 1984). The rock mass layers have been undulated, cut by a dense network of tectonic faults and, in addition, there are porphyry intrusions in the Carboniferous layers.

The largest faults are characterised by a throw of 300 m. In addition, there are numerous local faults, so-called seam faults with throws of up to several metres, in the coal-bearing strata. Carboniferous layers often form outcrops on the surface (photo: outcrops). The exploited hard coal deposit within the boundaries of the city of Wałbrzych lies from the surface to a depth of approximately 800m. It is a multi-deck deposit, with numerous seams of hard coal lying between layers of sandstone and clay shale. These are thin seams up to 1.5m thick, only a few are 2÷3m thick. The coal seams were exploited in several mines. In the area of the town of Walbrzych, east of the Chełmiec mountain, the seams have steep falls and form outcrops on the ground surface covered by a thin cover of Quaternary sediments (Figure 6).

Figure 6 - Carboniferous rock outcrops at the surface (M.Wysocka**)**

3.2 Topography

Sosnowiec

Sosnowiec is characterised by an interweaving of natural and anthropogenic forms, which have resulted from intensive industrial activity and urban development. The terrain of the city area is partly flat, partly hilly. Absolute heights range from +244.3 m above sea level (valley of the Czarna Przemsza River), to +310 m above sea level. The range of hills in the eastern part has the character of small domes, separated by small, shallow valleys. The surface descends towards the Czarna Przemsza and Brynica rivers.

The highest point of the city is an artificially raised ski slope in a park in the Środula district (approx. 310 m). A significant part of the city area is occupied by areas heavily transformed by man: numerous post-mining excavations of sand pits, quarries, clay pits and areas of shallow mining. There are also subsidence troughs from coal mining (up to 13 m deep) (Wagner et al., 2009), tailings and post-mining waste dumps, an extensive road system, excavations and embankments. The original character of the area has been significantly eroded mainly during urban development processes. The influence of mining exploitation has had a lesser impact.

Piekary Śląskie

The topography of Piekary Śląskie is characterized by a relatively flat landscape with some gentle hills. The city lies in the Upper Silesian Lowland, part of the larger Silesian Upland. The terrain is shaped by the Brynica River, which flows through the area, creating slight valleys. The highest natural elevation in Piekary is Winna Gora (350 m a.s.l.). Liberation Mound, which was mounded in 1932-1937, is the highest point in the city (356 m a.s.l.). The lowest point is the bottom of the Brynica River (261m a.s.l.) on the southeastern edge of the city The region is also influenced by past mining activities, which have affected the natural landscape. Overall, the topography is mostly low-lying, with some elevated areas, particularly in the western parts of the city. New landforms have appeared: humps, pits, bowls, basins, and most are tailings piles, ponds and sinkholes.

Wałbrzych

Within the boundaries of Walbrzych, there are geomorphological forms of fluvial, glacial, denudational and anthropogenic origin. Forms of fluvial origin - these are river valleys, e.g. of the Pełcznica River, flowing through the city. Forms of water-glacial origin - occur in the Pełcznica valley in the form of remnants of isolated patches of fluvioglacial sands and gravels. Forms of denudational origin - commonly found in the depressions of the area are clay deposits. Anthropogenic forms - associated with many years of underground coal mining, which ceased in the area in the 1990s. Their effect on the relief is a number of large heaps, as well as settling pits formed from waste created during mining (Figure 7 a,b).


a.

b.

Figure 7 a, b - Heaps and post-mining waste piles (M. Wysocka)

The closure of the coal mines in Walbrzych caused unemployment at the beginning of the 21st century, which was the main reason for carrying so-called ‘wild mining’. The waste piles, up to several metres high, and the pits in the aftermath of the bordering mines caused devastation of the ground surface.

3.3 Mining methods

Sosnowiec

In the 19th century mining depths did not exceed 40 m. The room and pillar system with caving was used. The capacity of drainage system of underground workings was limited.

In 1876 the modern deep mine Ludwig was founded, followed by Fanny. Both mines mined at a depth of approx. 80 m. In 1888 the two mines were merged at a depth of 80 m and later at a depth of

280 m. The mining system in use at the time was pillar with roof collapse. After World War I, shallow mining was briefly resumed and developed.

Hydraulic backfilling began around 1900. In 1925 longwall mining was introduced. From the interwar period onwards, hydraulic backfilling was used for about 50 years.

Hydraulic backfilling was used because of the geological conditions - thick seams, strong roof. In addition, the surfaces were protected from the effects of mining (subsidence, flooding), as mining was often carried out beneath buildings and industrial plants.

Seams 414 and 620 were mined with a collapsed roof. Seams 409, 501 and 510 were mined with both roof collapse and hydraulic backfilling. Deposit 501 was generally worked out in 1 layer (1.8 - 4.5 m), while deposit 510 was worked out in 2 or even 3 layers.

In the 1970s, the operating mines were modernised, leading to an output of approximately 8,500 tonnes/day. From 1970 onwards, mining with roof collapse using mechanised supports was used. From the 1970s, coal extraction steadily declined.

The Sosnowiec mines had 2-3 mining levels, 2-3 ventilation shafts and 2-3 peripheral shafts.

Piekary Śląskie

In Piekary Śląskie, zinc-lead ores have been exploited since the Middle Ages. Over time, mining techniques changed. From the Middle Ages until the end of the 19th century, ores were mined using the open-pit method in areas where the thickness of the Quaternary deposits was small, and the ore deposits lay at shallow depths. In the 16th to 18th centuries, in addition to the open-pit method, a method using multiple shafts and tunnels was employed, and less frequently, the chamber method. Shafts were drilled within small mining fields so that the main shaft was built in the center, with several additional shafts at the edges. Between these shafts, ore exploitation took place by drilling a network of tunnels. In the 19th century, the room and pillar method was introduced. Vertical and horizontal workings were abandoned after the extraction of ores deemed profitable at the time, or when water or dust inrush into the mine. New shafts were drilled near abandoned workings.

The coal seams, which outcropped at the surface, were locally subject to open-pit mining. Shallow shafts, several or dozens of meters deep, were also drilled around the outcrops. The mining system in use at the time was pillar mining with roof collapse. In the 1920s and 1930s, hydraulic backfilling began to be used, and longwall mining was introduced. Later, mining with roof collapse using mechanized supports became common. Coal mining was carried out using various systems, including the scavenging, stripping and longwall systems. Mining reached depths from 120 m to 780 m, and the thickness of the layers extracted was from 0.8 m to 6.5 m.

Wałbrzych

In the first historical stages of coal mining in Wałbrzych, coal was mined at a depth of 70-80 m from the surface. From the mid-18th century, shafts up to a depth of 50 m and adits were excavated, and mining was carried out by means of galleries. A significant development in coal mining took place in the 19th century, when hoisting machines powered by steam engines were used, and a rail network was used to transport coal on the surface.

In the 20th century, by 1944, hard coal production was already over 3 mln tons per year. The depth of exploitation in 1913 was about 500m, with 83 shafts in operation, and in 1934 the depth of exploitation was already 700m. After 1945, mining was carried out using the pillar and longwall method, mainly with roof caving, but also with dry and silt backfilling. In the final phase of the mines' operation, mining was carried out in protective pillars. The deepest, up to 880 m, was completed in 1986. Subsequently, the anthracite deposit was still being mined within the boundaries of the new mining area, which was liquidated on 26.06.1998. The mining operation was followed by the liquidation of the mines by flooding and most of the shafts by backfilling.

3.4 Number of mines/shafts/pits

Sosnowiec

Within the boundaries of the city at various times of its operation, 54 mines were in operation. There were approximately 207 shafts and colliery adits. Most of them were small shallow, up to 80 m. The following mines have been in operation in Sosnowiec in recent years: Sosnowiec, Porąbka Klimontów, Niwka Modrzejów, Kazimierz Juliusz and partly Saturn, Siemianowice and Paryż – (Figure 8). The depth of operation was up to 500m.

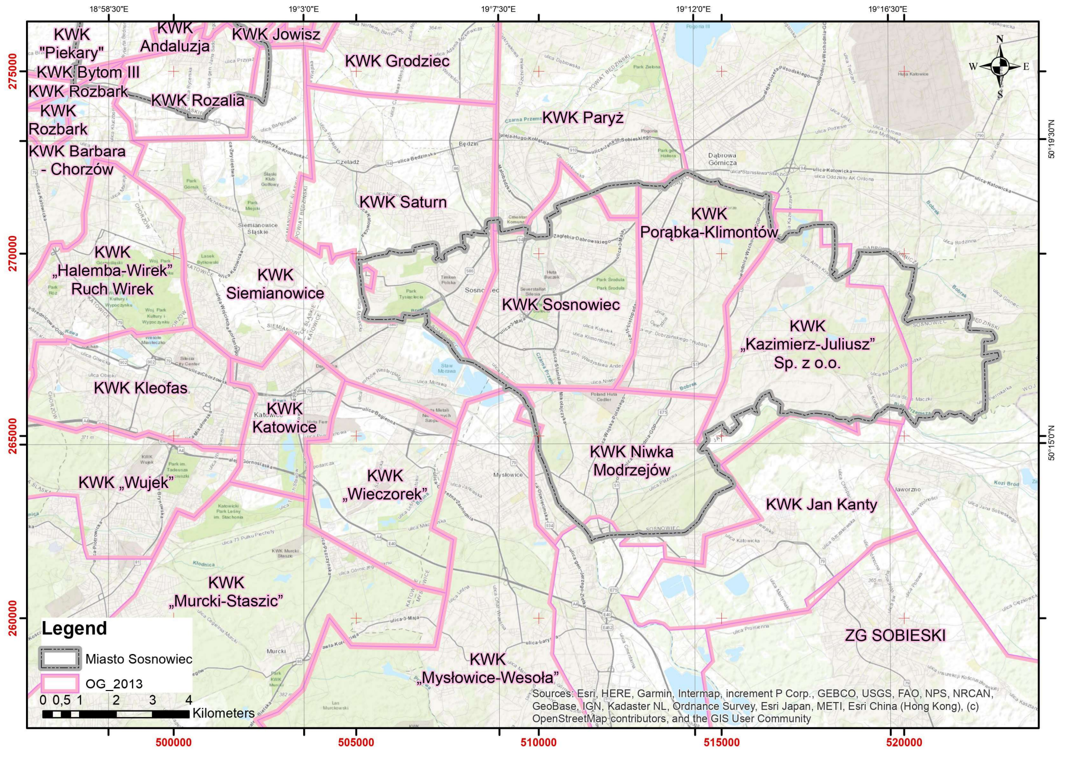

Figure 8 - Coal mines within the boundaries of Sosnowiec

Piekary Śląskie

Already in the Middle Ages, due to the intensive exploitation of zinc and lead ores, 20,000 mine shafts were counted in Piekary Śląskie. Currently, within the city's administrative boundaries there are 336 documented excavations, shafts and pits connected to the surface.

In recent years 5 coal mines were operating in Piekary Śląskie: Jowisz, Piekary, Powstańców Śląkich, Rozbark and Siemianowice – (Figure 9).

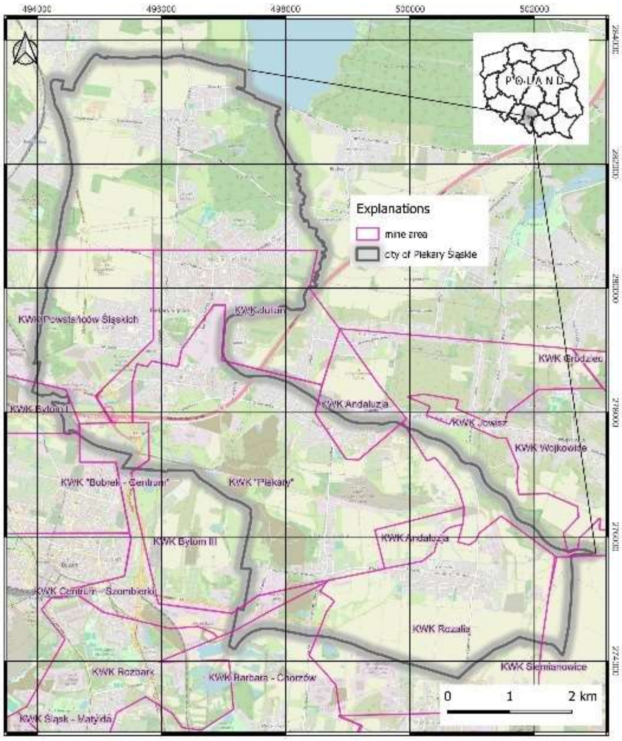

Figure 9 - Coal mines within the boundaries of Piekary Śląskie

Wałbrzych

In 2018, an inventory of pits in contact with the surface was carried out, which showed that in Wałbrzych and its vicinity, there were 669 pits, mostly shallow shafts to a depth of 20-40 m, and adits. The site visit and analysis of potential hazards posed by the presence of the pits showed that 24 pits posed a potential safety risk to area users and would require safety measures. In most cases, the hazard was identified as low or medium (Kowalski et al. 2016). In recent years 3 coal mines were operating in Wałbrzych: Wałbrzych, Julia, Victoria – (Figure 10).

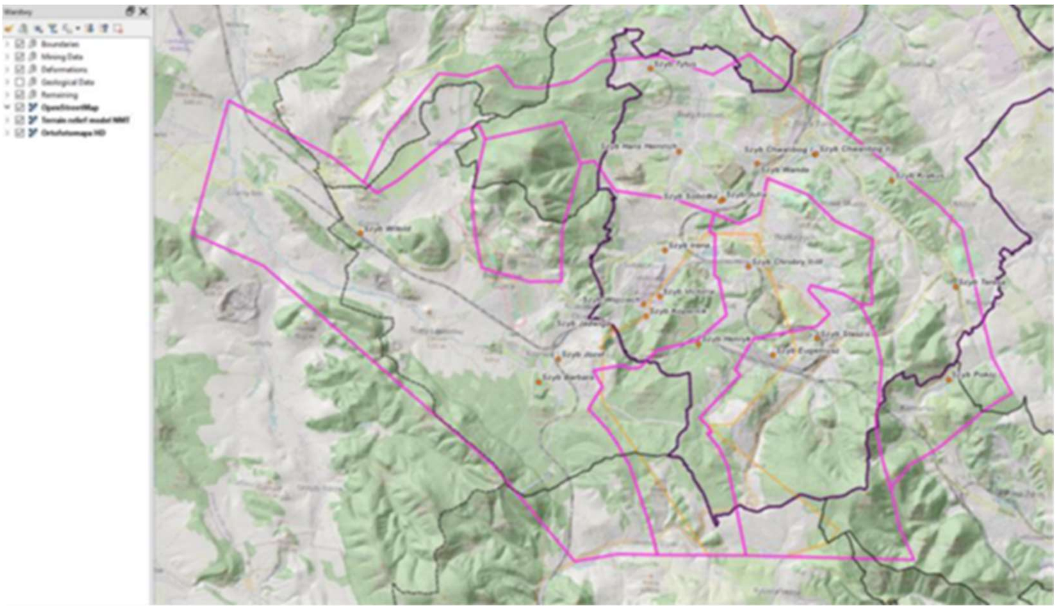

Figure 10 - Coal mines within the boundaries of Wałbrzych

3.5 Time of operation

Sosnowiec

The history of coal mining in the areas now belonging to Sosnowiec is very rich and dates back to the end of the 18th century. Sosnowiec is a mining town and from the middle of the 19th century its development was linked to coal mining, iron and zinc metallurgy, textile industry and trade developing in the border area. The town's proximity to the national borders promoted industrial investments financed by Polish, Russian, German and Italian and French capital. Almost 80% of the city's area was under the direct or indirect influence of mining exploitation. Since the beginning of the 19th century, there have been 54 coal mines operating within the current boundaries of the city, while the only mine with mining operations until recently, i.e. 29 May 2015, was ‘Kazimierz-Juliusz’. The first mine, ‘Hope Ludwig’, was founded in 1806. From 1817, underground coal mining began in the mine. It operated until 1864. It exploited seams up to a depth of 40 m.

In the early years of mining numerous tunnels, shafts were constructed in order to access new shallow coal seams, which caused numerous accidents. One of the biggest mining catastrophes in Sosnowiec was the flooding of the excavations of the ‘Ludmiła’ mine in 1880 by dust and water from the nearby Czarna Przemsza river.

At that time the following mines were operating in Sosnowiec: Sosnowiec, Porąbka Klimontów, Niwka Modrzejów, Kazimierz Juliusz and partly Saturn, Siemianowice and Paryż.

After the political transformation after 1989, as part of the government's mining restructuring programme, a process of gradual liquidation of individual mining plants took place. It was assumed that the coal mines would be liquidateded between 1995 and 2004. In fact, the last mine was liquidated in 2015.

Piekary Śląskie

The shallow exploitation of zinc and lead deposits began as early as the 12th century and continued, with various stages of mining technology development, until 1989.

The coal mines operated from the late 19th century. The first mines ("Radzionków" and "Rozbark") began exploitation in 1863 and 1870 and operated until 1975 and 1990. The next mines began exploitation in the early or mid-20th century. As a result of the restructuring of the mining industry, many mines were closed or merged into larger companies.

The complete liquidation of the last coal mine was finalized in 2021.

Wałbrzych

The origins of coal mining in Wałbrzych date back to the 16th century. At that time, hard coal was mined on the outcrops of the seams, opencast in pits and in dugouts to a depth of around 10m. Underground mining began in the mid-18th century. In the mid-19th century, hoisting machinery was introduced and mining intensified. By the mid-20th century, mining reached levels at depths of up to 500m. After the Second World War, mining went down to 880m.

Exploitation was terminated on 26.06.1998. After the end of mining, the mines were liquidated by flooding and most of the shafts were filled in.

4 Identification of the hazards

4.1 Post-mining hazards in Sosnowiec

Approximately 80% of the town of Sosnowiec is affected by mining. Only 17% of the former mining area, where in turn shallow mining was concentrated, is unaffected.

The knowledge base, describing the different hazards that can affect areas of active and abandoned mines was prepared within the WP2 Post mining hazards and multi hazard identification and assessment methodology, Task 2.1.

4.1.1 Discontinuous and continuous deformations

Discontinuous deformations

The risk of sinkholes and ground subsidence exists in areas where coal mining was carried out in the outcrop coal beds. The greatest hazard exists in the areas of shallow exploitation of the coal bed 510 due to significant thickness of the extracted layer. In the areas of old workings, discontinuous deformations of the ground surface still occur today, leading to the formation of funnels, sinkholes (Figure 11) or cracks, fissures and thresholds (faults). These movements are related to the instability of the rock mass caused by the presence of voids in the rock mass (shafts, shafts, sidewalks) (Jankowski, ed., 1994) and/or their improper liquidation in the rock mass.

Figure 11- The sinkhole created on playground (www. Miasto Sosnowiec**)**

The formation of discontinuous deformations is a consequence of suffusion processes, causing the leaching of sandy material from strata lying in the Carboniferous floor. These processes are particularly intensive in river valleys filled with sandy formations. The presence in the overburden of laminated Triassic sediments also promotes drying phenomena. In general, the areas with a connection to the surface are potentially at greatest risk. Other areas at risk are areas of shallow mining, especially the edges of mined out parcels, especially in river valleys, due to possible drift phenomena. The largest number of sinkholes were created in the southern part of the city, within the boundaries of the Niwka Modrzejów and Sosnowiec mines. A smaller number of sinkholes were located in the northern part of the city, within the boundaries of the Paris and Kazimierz Juliusz mines. The areas of sinkholes coincide with areas of shallow mining, less than 100 m below ground level (Figure 12). In addition, both in the northern and southern parts of the city there is a particular concentration of shafts, adits and other connections with surface. Figure 13 illustrates the prepared map of sinkholes in Sosnowiec.

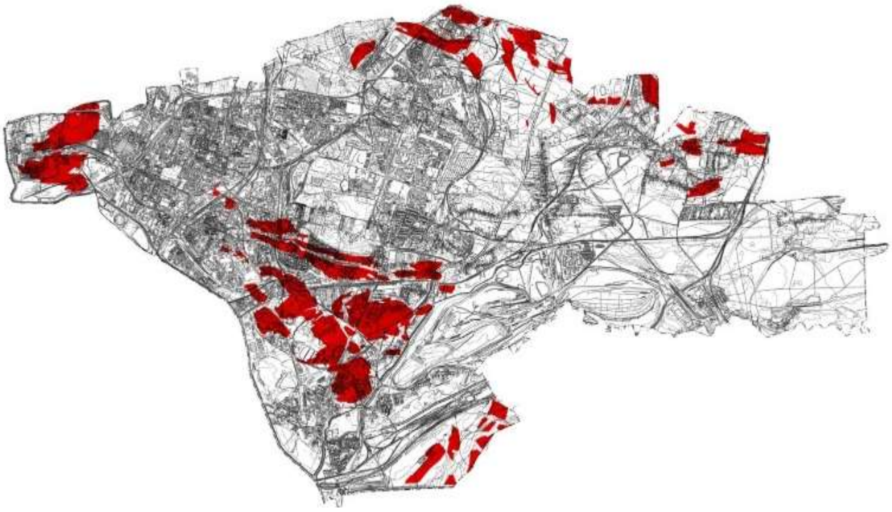

Figure 12 - Shallow (up to 80 m) exploitation in borders of Sosnowiec (scale 1:125 000), from the resources of the city archive

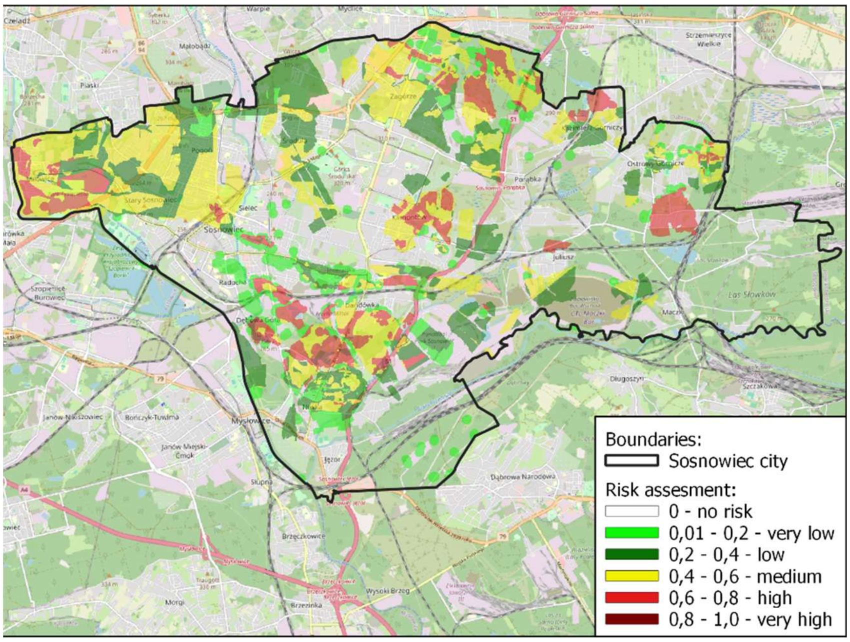

Figure 13 - Discontinuous deformations risk map in Sosnowiec (scale 1:125 000)

Continuous deformations

New geomorphological processes are taking place in the city area, including continuous deformation.). Figure 14 illustrates the map of vertical deformation.

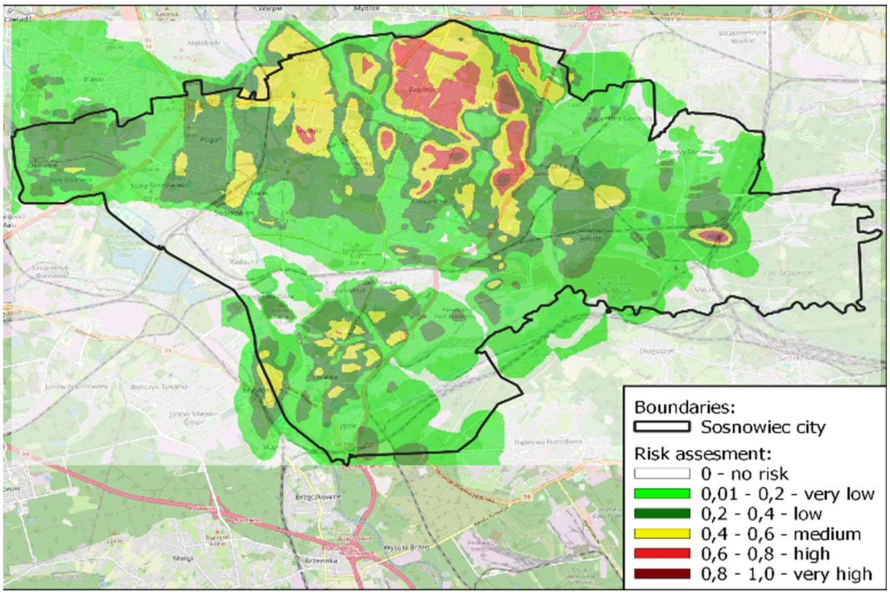

Figure 14 - Vertical deformation – subsidence risk map in Sosnowiec (scale 1:125 000)

4.1.2 Mine induced flooding, hydrogeological disturbances

The places of mining subsidence are generally filled by floodplains. Some of them are developed and perform recreational, livestock or ecological use functions. Within the city, 81 floodplains have been identified: 21 were created by subsidence of the land surface, 60 were created in excavations post-exploitation pits (Wagner et al, 2009, Węgrzynek, Sokół, 2019). Floodplains are found in the southern part of the town, by the Bobrek river, in the northern part, in places of historic shallow coal mining and partly along the western boundaries of the town.

A serious problem is the area of the recultivated excavation of the strip mine - Maczki. -Bór. The floodplain in the vicinity of Maczki was found to reach 11 m. Figure 15 illustrates the map of floodplains in Sosnowiec.

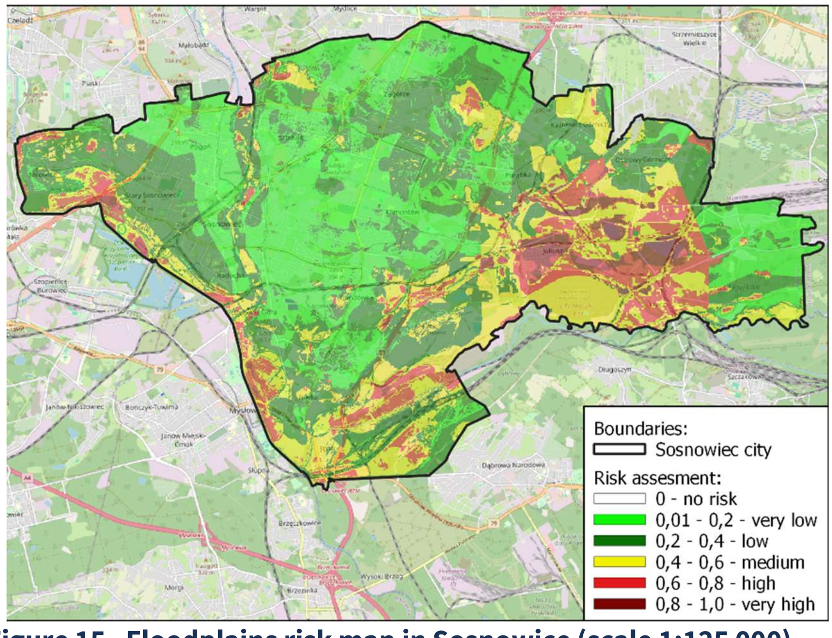

Figure 15 –Floodplains risk map in Sosnowice (scale 1:125 000)

A problem in the future will be the impact on the hydrogeological conditions of the Maczki-Bór sand mine area. Currently, the water table is lowered by 20 m and the water is pumped out from under the waste dump near the mine. The city plans to build pumping stations in the areas most prone to flooding.

Ionizing radiation

The investigations and measurements performed in Upper Silesia for more than 20 years have shown that the enhanced radon concentrations in soil gas and in dwellings are measured in sites in areas heavily transformed by coal mining, over mining voids, in the vicinity of shafts, shallow mine workings, etc, (Figure 16). One of the output WP 2, Task 2.3 “Development of methodology for post-mining hazards interaction identification” was (between others) “Radon tool”. The developed tool allows radon risk assessment based on detailed analysis of geological, mining and environmental information.

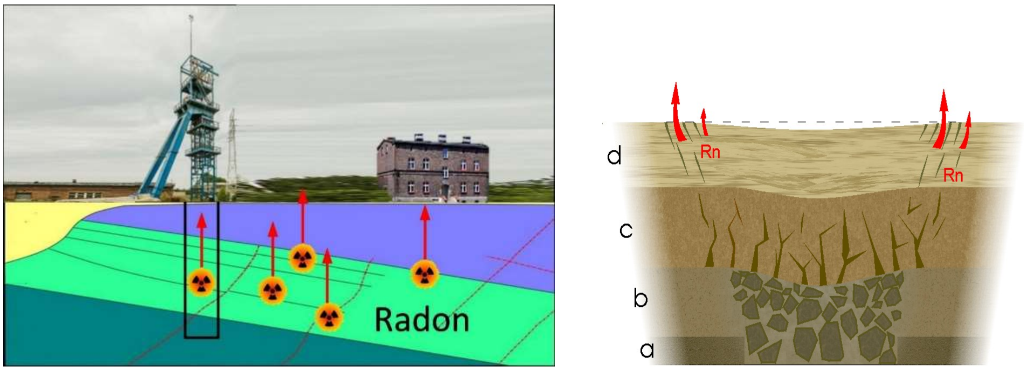

Figure 16 -A schematic illustration showing the pathways of radon ingress into buildings in post-mining areas

Considering the fact that within the boundaries of Sosnowiec there are conditions resulting from mining activities that favor the migration of radon, using the ‘radon tool’, we made a theoretical estimate of the city's radon potential. The result showed that there is a probability that a certain number (percentage) of buildings may have elevated radon concentrations. Measurements were carried out in a number of schools selected by the city. The results of the measurements showed that the average radon concentration exceeds the average value for the USCB. In the basements, concentrations exceeded the recommended value of 300 Bq/m^3. This means that the radon risk was underestimated in our assessments. The city was suggested to pay more attention to the potential risk of exposure of residents to increased radon concentrations in buildings. Basing on performed measurements and assessments the map of radon hazard was developed, (Figure 17).

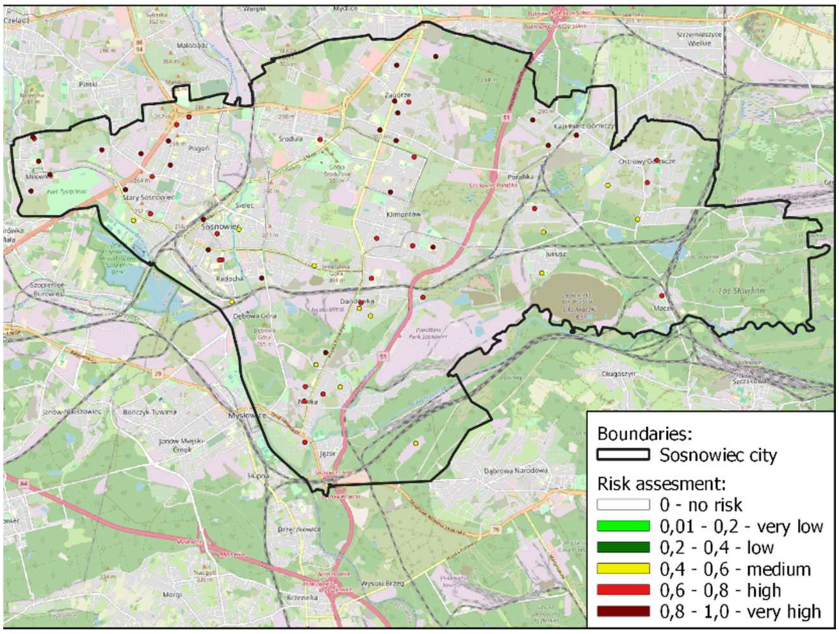

Figure 17 - Radon emission risk map in Sosnowiec (scale 1:125 000)

4.2 Post-mining hazards in Piekary Śląskie

4.2.1 Discontinuous and continuous deformations

Exploitation at great depths led to the formation of continuous deformations in the form of gentle and extensive depressions of the terrain – subsidence basins. In the Piekary Śląskie area, this phenomenon has a very large spatial range. The course of land subsidence is relatively slow, and after reaching equilibrium, subsidence gradually ceases. The basins, usually waterlogged, have irregular contours and an uneven profile of the bottom and slopes. Historically, coal exploitation was particularly intensive in the southern and western parts of the city. The thickness of extracted seams ranged from 20 to 33 m. The share of backfilling was from 10% to 60%, depending on the region. The maximum depression of the terrain in places of such intensive exploitation was up to 16 m.

The formation of these subsidence basins was often accompanied by the formation of small-scale discontinuous deformations. Figure 18 presents map of continuous deformations in Piekary Śląskie.

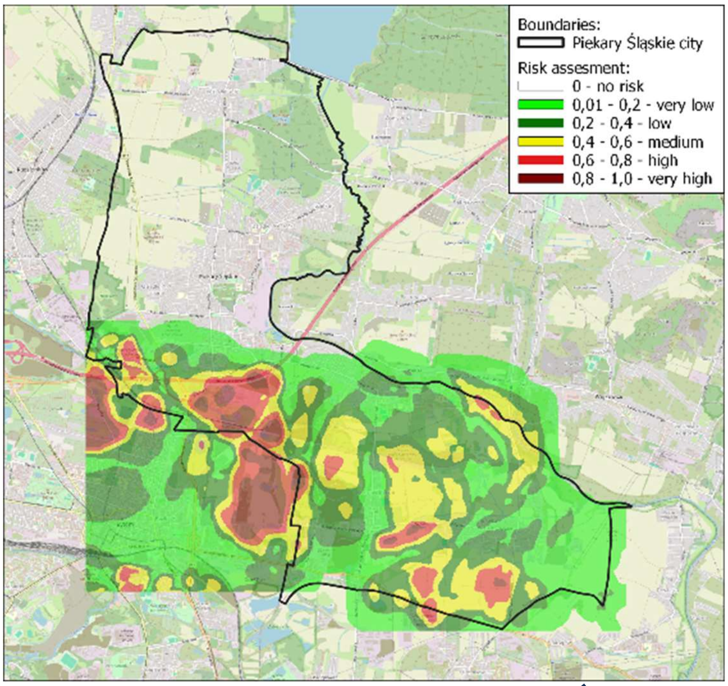

Figure 18 - Continuous deformations risk map in Piekary Śląskie (scale 1:100 000)

In previous years, expert assessments were carried out, which allowed for the identification of so-called calmed areas and areas at risk of deformation. Unformed mining voids can lead to terrain deformation, especially with urban development load or surface water infiltration. A particular risk is posed by excavations connected to the surface, which make safe development difficult. Due to the lack of full documentation of the liquidation of shafts and post-mining voids, old excavations may pose a hazard to the stability of the ground surface and buildings. Incorrectly liquidated and uncolmatized (unsealed) old, historical workings of great height and width or shafts contribute to the occurrence of discontinuous deformations such as cracks, crevices, ditches, sinkholes. These sinkholes arise suddenly and their development results from the weakening of the roof of the workings as a result of processes such as suffosion, dissolution, leaching, spontaneous combustion or relaxation movements of the rock mass. Development in these areas requires detailed geotechnical studies and appropriate ground conditioning. The map of discontinuous deformation in Piekary Śląskie is shown on Figure 19.

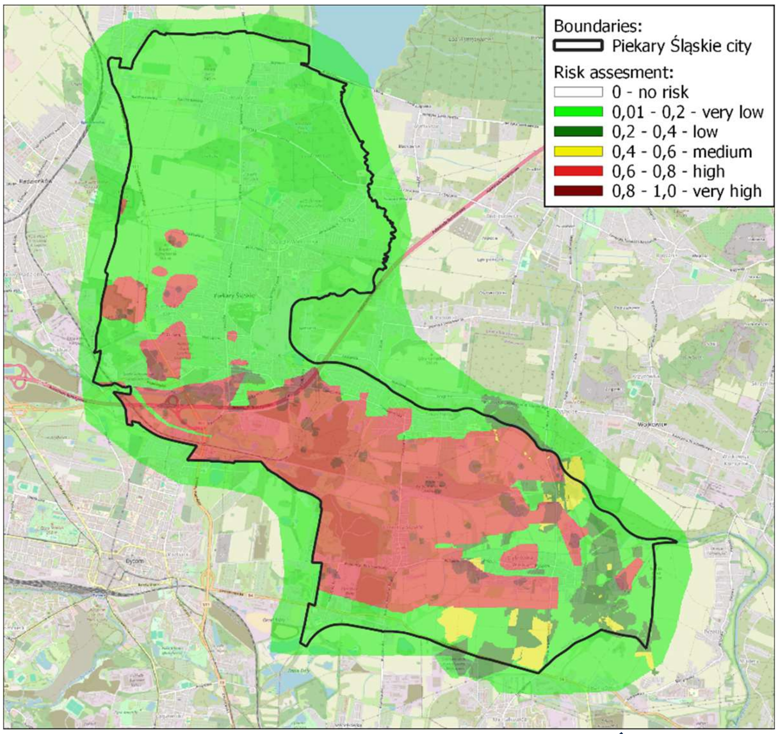

Figure 19 - Discontinuous deformation risk map in Piekary Śląskie (scale 1:100 000)

4.2.2 Mine induced flooding, hydrogeological disturbances

Intensive mining activity in Piekary Śląskie has caused a very serious changes of transformation of the natural environment. The part of land in the southern and southwestern districts of the city has been lowered by several meters due to continuous deformation of the terrain. Drainage of the rock mass in order to make deposits available has resulted in the depletion of water resources of the Triassic and Quaternary aquifers. This has resulted in a lowering of water quality. Large amounts of pumped mine water containing zinc and lead ions were introduced into surface waters, which resulted in the concentration of these metals in bottom sediments. Terrain deformation and poor water quality have resulted in the need to canalize surface streams. For example, the Jowisz coal mine led to the subsidence up to 10 m deep in the Brynica valley, which forced the construction of high embankments and the relocation of the river bed. In general, the deformation of the terrain and the drainage of underground waters caused a significant disruption of the circulation of surface waters, which lost their natural bonds, through the regulation and sealing of the river bed, the introduction of high embankments necessary due to the lowering of the neighboring areas, the relocation and partial covering of the river bed. Figure 20 presents map of floodplains in Piekary Śląskie.

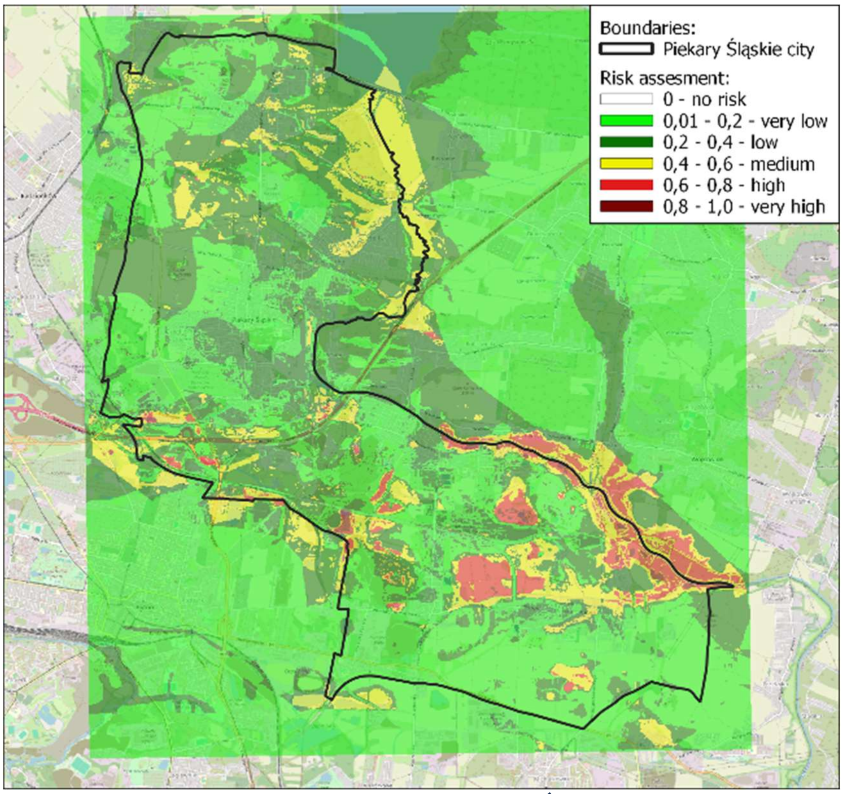

Figure 20 -Floodplains risk map in Piekary Śląskie (scale 1:100 000)

Ionizing radiation

In mining and post-mining areas, elevated radon concentrations in buildings are often measured. Areas at particular risk are those where both shallow and deep mining have taken place and where the geological structure allows gas migration. That is why studies of this hazard have been carried out for many years in Piekary Śląskie (Chałupnik, Wysocka 2003, Wysocka 2016, Wysocka et al. 2019, Wysocka et al. 2022). The analysis of the results of measurements, conducted last years in Piekary Śląskie, confirmed the hypothesis about the primary influence of the local geological structure on the distribution of radon levels in buildings. However, changes in the rock mass, resulting from coal mining (presence of voids, subsidence, lowering of the water level, rejuvenation of faults, etc.) accelerate the phenomena of surface erosion and karst development, which creates pathways for more intense gas migration. In post-mining regions, areas with an increased radon risk occur not only directly above mining excavations or subsidence zones, but also everywhere where rock mass disintegration leads to erosion and karst formation. Map of the radon hazard in the city is presented on Figure 21.

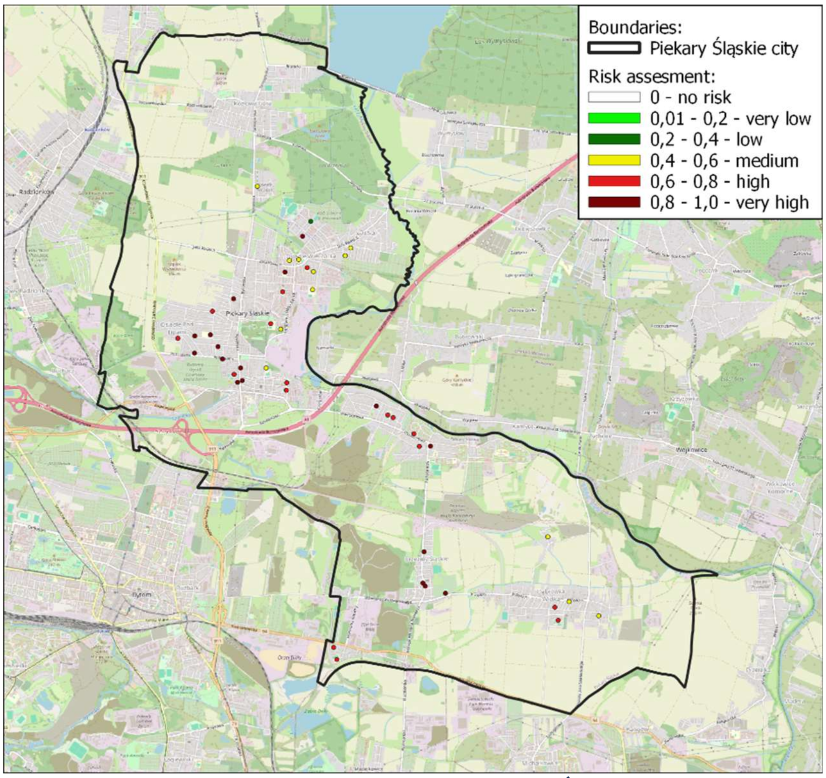

Figure 21 -Radon emission risk map in Piekary Śląskie (scale 1:100 000)

4.3 Post-mining hazards in Wałbrzych

4.3.1 Discontinuous and continuous deformations

Discontinuous and continuous surface deformation, concentrated in the southern part of the current city borders (Figure 25). Discontinuous deformations are revealed over shallow mining operations carried out at depths of less than 80 metres from the surface. They manifest themselves in the form of: ground sinkholes (regular or irregular funnels), terrain sills, fissures and cracks in the terrain. The effect of mining activities on the surface was continuous deformation, which occurred in the form of subsidence basins and indicators derived from them, as well as linear discontinuous deformation of the surface in the form of fissures and steps. In Wałbrzych in the period of the final phase of the disclosure of impacts on the ground surface due to mining exploitation, are the disappearing deformations, the so-called residual vertical displacements. In the case of the Wałbrzych, where the old goaf and rock mass were flooded, i.e. the dewatering pumps were turned off after the mines finished coal extraction, both phenomena of residual vertical displacements are observed: subsidence and uplift of the surface (Kłyż J., Kłyż R. 2024).

The largest depressions observed by surveying methods were up to 17.3 m for the period from 1916 to 1996. The largest were measured up to 7 m, while in the downtown area of Walbrzych, depressions are up to 0.3 m (Figure 23).

The flooding of goafs began in the downtown area of Wałbrzych in 1994, and was completed in 2002, when water from the rock mass flowed into the Friedrich-Wilhelm drainage adit, and then piped into the Pełcznica River. The process of goaf flooding was monitored in piezometers in the accessible shafts and in boreholes on the surface. After the goafs were flooded, uplifts of the ground surface occurred, which in the monitored area amounted to about 0.15 m, representing 8 % of the previously measured subsidence. Measurements made in 2024 confirmed the occurrence of uplift of the ground surface. It was estimated that uplifting occurred around 2000, i.e. about 2-4 years after the end of mining operations.

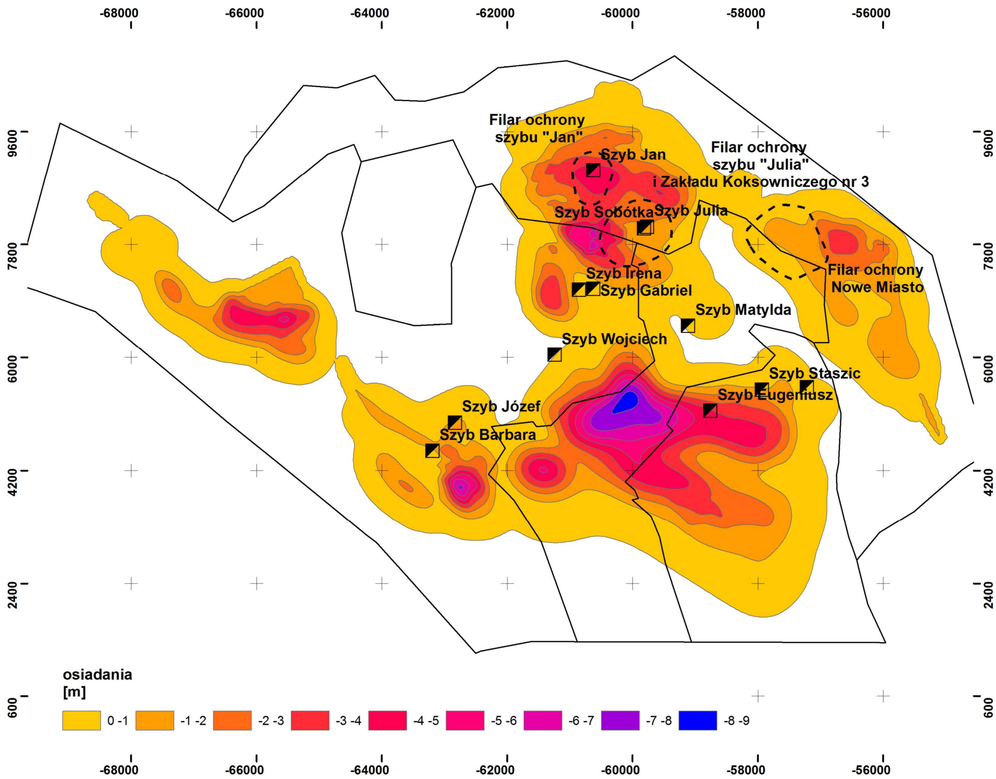

Figure 22 -Surface subsidence of the WKWK area in the period 1945-1996 (Kowalski A., 2000)

Figure 23 - The example of continuous surface deformation (M.Wysocka)

4.3.2 Mine induced flooding, hydrogeological disturbances

There were depressions in the form of subsidence basins above the coal mining areas. Floodplains formed in the basins.

Throughout the whole period of coal exploitation, disturbances in water regime occurred, manifested by the drainage of aquifers in the rock mass. Liquidation of the mines triggered further adverse phenomena, resulting from the reconstruction of the original water table in the rock mass (Supel et al, 2012). The process of reconstruction of the water table may cause further areas of local flooding, especially in the absence of an unobstructed drainage system (Figure 24).

Figure 24 - Flooding, discharge of mine water into the Pełcznica River (M.Wysocka**)**

4.3.3 Gas and ionising radiation hazards.

A negative effect of the liquidation of the mines was the gas hazard, a phenomenon involving the accumulation and migration of mine gases in the workings and the surrounding rock mass, which were displaced to the ground surface by the rising water table in the Carboniferous (the 'piston effect'), as well as the effects of pressure and temperature gradients. To monitor this hazard, methane and carbon dioxide concentrations were measured in boreholes about 2 m deep, as well as in the lowest floors of buildings.

A particular problem in Wałbrzych, in terms of gas hazards, are old workings (shafts, galleries and adits) close to the surface, where the content of carbon dioxide and methane in the air can exceed acceptable standards (Figure 25). A series of measurements of methane, carbon dioxide and radon concentrations were taken in 2024 (Figure 26 and Figure 27). Measurements performed have shown that:

- Elevated concentration of methane and CO_2 were measured in „Lisia Sztolnia" (adit) site and in shafts outlet air.
- Elevated concentrations of these gases were not measured in open air and in areas of shallow mining, surface discontinuities and porphyry outcrops.
- Elevated concentration of gases was not measured in basements of residential buildings were also taken.
- The oxygen concentration is comparable to average values in the air.

Figure 25 -Degassing well (M.Wysocka)

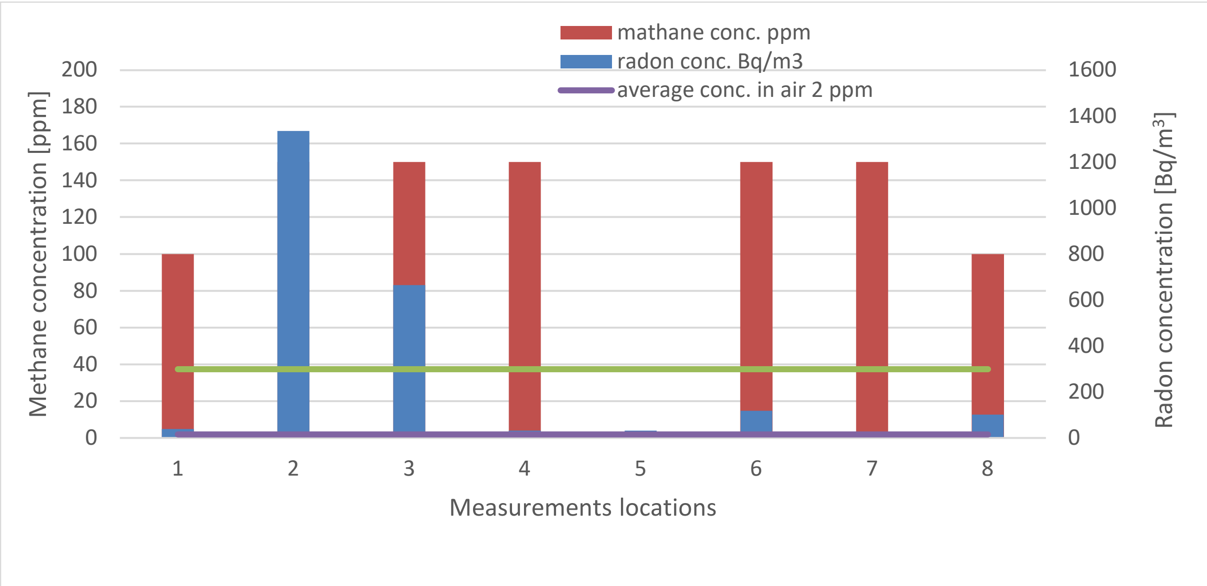

Figure 26 -Results of mesurements of radon and methane concentration in post mining instalations (outlet of shaft, adit)

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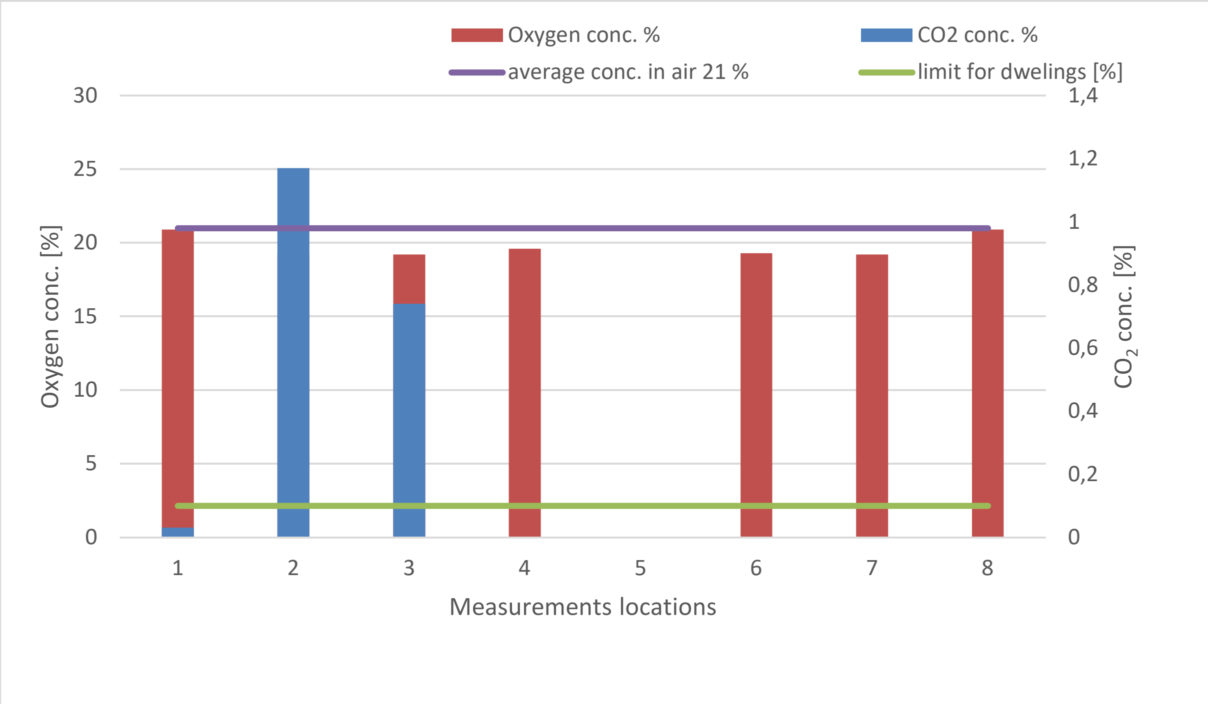


Figure 27 -Results of measurements of oxygen and CO2 in post mining installations (outlets of shafts and adit)

Results of the performed measurements radon concentration have shown that:

- High concentrations of radon have been measured in areas such as shafts and adit outlets – up to 1335 Bq/m^3.
- Elevated gas concentrations were not measured in areas of shallow mining, surface discontinuities and porphyry outcrops.
- Measurements of radon concentrations in residential buildings were also taken. The measured concentrations ranged from about 20 to about 120 Bq/m^3. In no case did radon concentrations exceed the recommended value, 300 Bq/m^3.

4.4 Identification of the natural and technological hazards (maps and tables, based on the Pomhaz outcome)

The hazards occurring in the areas of interest of the project have been identified. Their nature has been specified as natural, mining-related, or artificial. Interactions between the individual hazards have been analyzed, with a focus on preliminary and secondary hazards. For each of the cities, an analysis of the significance/importance of each identified risk was conducted. Due to the fact that the geological, mining, and technical conditions vary in each city, discussions were held with specialists from the cities, GIG, and SRK. The significance of each hazard was indicated on a scale from 1 to 3 (see tab. 1).

Table 1 - Hazards and their significance in 2 cities of Upper Silesian Coal Basin (GZW) and Wałbrzych, Poland

	How important? Scale: 3 – very important; 2 – less important; 1 – unimportant or very rare		
Hazard	Partner city		
	Piekary Śląskie	Sosnowiec	Wałbrzych
Subsidence	2	2	1
Settlement	1	1	1 --- 2
Discontinuous deformations – crevices	1	1 --- 2	3 --- 1
Discontinuous deformations – sinkholes	3 ---- 2	2 --- 3	3 --- 2
Slope movement (slope stability)	1	1	1
Rock falls	1	1	3
Induced seismicity	1	1.--- 2	1
Environmental water pollution	1	1 --- 2	3
Hydrological disturbances, mining induced floods	1 --- 2	3	3
Environmental pollution from spoils	1	1/2	3
Exposure of residents to increased radon concentrations in buildings	1 ---- 2	1 --- 2	1
Gas emissions linked to mining	1	1	3 --- 1
Combustion and overheating of mine waste	1	1	3

The significance categories of some risks changed after subsequent stages of discussions and research.

The changes in the ranking of hazards significance in Piekary Śląskie.

- **Sinkholes** were considered as the most important problem in Piekary Śląskie site. After analysis we decided to lower the importance rating from 3 to 2. The next hazard underlined was related to **subsidence** and the rate was not changed.
- Using the ‘radon tool’, we made a theoretical estimate of the city's radon potential. The result showed that there is a probability that a certain number (percentage) of buildings may have elevated radon concentrations. Measurements were carried out in a number of schools selected by the city. The obtained results suggest that the potential risk of **exposure of residents to increased radon concentrations in buildings** may pose the problem for the city. The rate was changed from 1 to 2.

- In our opinion the hazards related to **hydrological disturbances and mining induced floods** were underestimated, more emphasis should be placed on this problem in our further work. The rate was changed from 1 to 2.

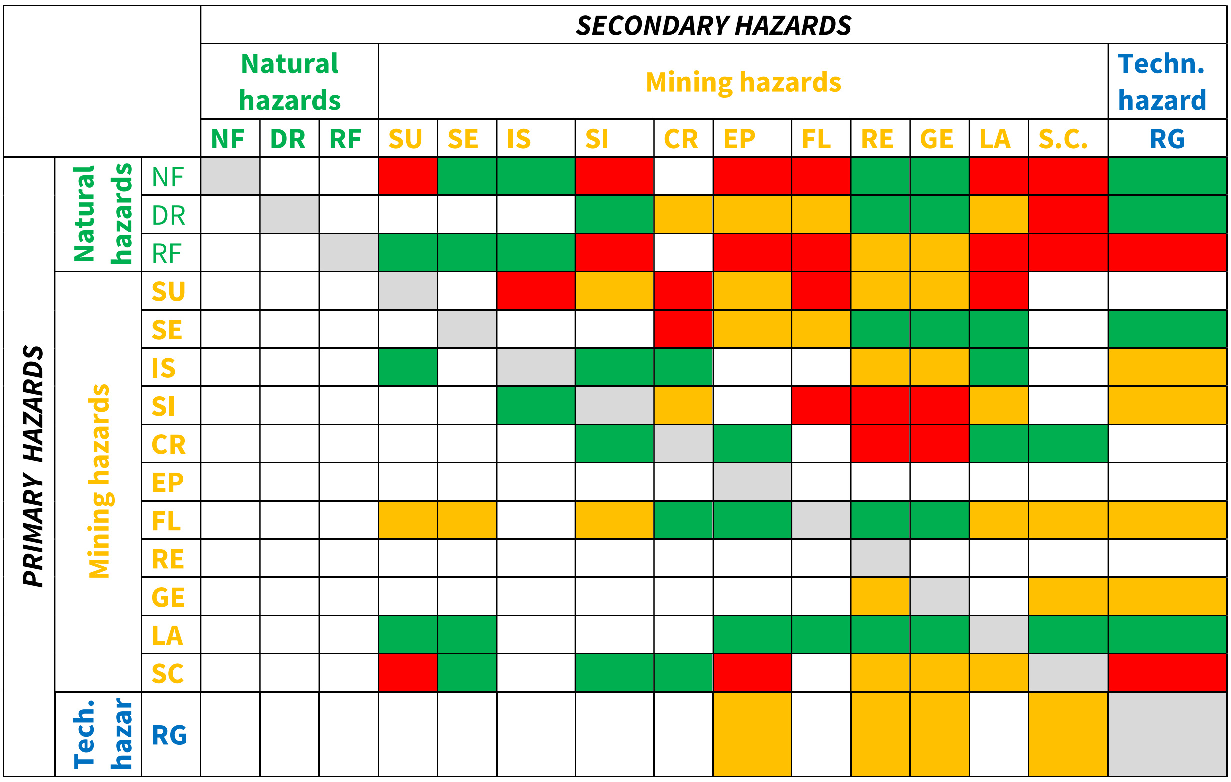
The changes in the ranking of hazards significance in Sosnowiec.

- **Hydrological disturbances and mining induced floods** were considered as the most important problem in Sosnowiec site. In the future, environmental water pollution and occurrences of induced seismicity can be expected, related to the stabilization of the water table over a long period of time after the flooding of closed mines. Ranks were changed from 1 to 2.
- In discussions with representatives of the city, it was agreed that the hazard related to discontinuous deformations – **crevices** and **sinkholes** should be highlighted more strongly. So far these phenomena are not frequent, but have been occurring for some time. The municipal services are concerned that this hazard may be significant in the future. The rates were changed from 1 to 2.and from 2 to 3 respectively.
- Using the ‘radon tool’, we made a theoretical estimate of the city's radon potential. The result showed that there is a probability that a certain number (percentage) of buildings may have elevated radon concentrations. Measurements were carried out in a number of schools selected by the city. The results of the measurements showed that the average radon concentration exceeds the average value of the for GZW. In the basements, concentrations exceeded the recommended value of 300 Bq/m^3. This means that the radon risk was underestimated in our assessments. The city suggests paying more attention to the potential risk of **exposure of residents to increased radon concentrations in buildings.** The rate was changed from 1 to 2.

The changes in the ranking of hazards significance in Wałbrzych.

- We originally considered the hazard of increased gases emissions to be of key importance for the town's residents. Next indicated problem was **vertical surface displacements** (subsidence, uplift of the surface). To verify our approach, after discussions with experts from the city, we decided to perform measurements of gases concentrations and values of the vertical surface displacement. We found out that gases emissions (radon, methane CO_2) were lower than expected and limited to inaccessible areas such as shafts and adits. The rank was changed from 3 to 1.
- Discontinuous deformations – crevices and sinkholes – are of lesser significance than initially assumed. The rank was changed from 3 to 1 and from 3 to 2 respectively.
- The most important hazards in Wałbrzych are hydrological disturbances and mining induced floods e.g. mining subsidence basines filled by floodplains.

The matrix below illustrates the results of the interaction analysis conducted for the Upper Silesia region (Poland). The analysis takes into account specific local geological and technical conditions (Figure 28).



Levels of interaction: high interaction; intermediate interaction; low interaction; no interaction (white)

Hazard: NATURAL FLOOD (NF), DROUGHTS (DR), RAINFALL (RN); SUBSIDENCE (SU), SETTLEMENT (SE), INDUCED SEISMICTY (SE), SINKHOLES (SI), CREVICES (CE), ENVIRONMENTAL POLLUTIONS FROM SPOILS (EP), HYDROLOGICAL DISTURBANCES, MINING INDUCED FLOODS (FL), RADIATION EMISSION (RE), GAS EMISSION LINKED TO MINING (GE), LANDSLIDE (LA), SELF COMBUSTION (SC); GASES EMMISION FORM SPOILS, HEAPS (RG)

Figure 28 -The risks matrix

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

With the information and data collected in the implementation of WP 2, Task T2.1, a matrix of interaction was made in all case sudies for the most relevant risks. The developed matrices are presented below (Figure 29, Figure 30 and Figure 31). The significance of the correlations is discussed. The factors influencing the results of the analysis have been analysed. The conclusions are highly relevant for spotting future work on risk and multi-risk estimation in post-mining areas.

Sosnowiec

	hazards	determinants					
		radiation emission	sinkhole	mining induced floods	deformations	self combustion	environment pollution from spoils
secondary hazards	radiation emission	X	0,36	-0,26	0,07	0,00	0,00
	sinkhole	0,00	X	-0,08	0,54	-0,11	0,00
	mining induced floods	0,00	-0,08	X	-0,02	0,00	0,00
	deformations	0,00	0,54	-0,02	X	-0,24	0,00
	self combustion	0,00	-0,11	0,00	-0,24	X	0,00
	environment pollution from spoils	0,00	0,08	0,00	-0,16	0,29	X

correlation coefficient r	correlation
[-0.2 - 0.2]	very weak/negligible
(-0.4 - -0.2]+[0.2 - 0.4)	weak
(-0.7 - -0.4]+[0.4 - 0.7)	average
(-0.9 - -0.7]+[0.7 - 0.9)	strong
[-1.0 - 1.0]	very strong

Figure 29 -Matrix of interaction for Sosnowiec

Analysis of the risk matrix allows the relationship between risk determinants and their effects in post-mining areas to be assessed. Risk determinants include radon emissions, sinkholes, flooding, land deformation and heap leach hazards such as fires and emissions. The effects of these processes take into account both geological changes and potential environmental risks. The results of the analysis indicate that, within the Sosnowiec city borders, most of the correlations reach values below 0.3, which means that no clear correlations between the analysed factors have been demonstrated. In such cases, the influence of determinants on the possibility of other hazards may be coincidental or dependent on other variables not included in the model. However, in a few cases, clearer relationships were observed. The strongest relationship concerns the relationship between sinkholes and land deformation, where a correlation of 0.54 indicates a medium relationship. This is not surprising - areas where sinkholes occur are naturally prone to land surface deformation (and vice versa). Rapid ground subsidence leads to cracks, fissures and local subsidence, which can affect both the infrastructure and hydrological conditions of the region.

Although it is interesting to point out the low correlation between radon emissions and sinkholes, of 0.36, this may indicate that under certain conditions the instability of the terrain favours the release of the gas into the atmosphere. System of post mining voids and fissures in the rock mass may form fracture systems that facilitate radon migration, which could explain this relationship.

Other correlations, including those relating to the impact of heaps on other hazards, did not show significant relationships. This could mean that heap processes, such as fires or emissions, have limited impact on the soil mechanics in the study area. Although the statistical analysis did not show a significant correlation between heap fires and pollutant emissions, from the point of view of geochemical and environmental processes, this is a real threat, the impact of which may be visible over a longer period of time or over larger areas. The lack of statistical correlation in the matrix may be due to several factors, e.g. limited measurement coverage, other sources of pollutant emissions, local differences in heap composition.

The lack of correlation between some hazards is also due to a lack of sufficient data to perform the relevant calculations.

Piekary Śląskie

	hazards	determinants: radiation emission	sinkhole	mining induced floods	deformations	self combustion	environment pollution from spoils
secondary hazards	radiation emission	X	0,26	-0,11	-0,01	0,00	0,00
	sinkhole	0,00	X	0,19	0,30	0,00	0,00
	mining induced floods	0,00	0,19	X	0,52	0,00	0,00
	deformations	0,00	0,30	0,52	X	0,00	0,00
	self combustion	0,00	0,00	0,00	0,00	X	0,00
	environment pollution from spoils	0,00	0,33	0,00	0,88	0,00	X

correlation coefficient r	correlation
[-0.2 - 0.2]	very weak/negligible
(-0.4 - -0.2]+[0.2 - 0.4)	weak
(-0.7 - -0.4]+[0.4 - 0.7)	average
(-0.9 - -0.7]+[0.7 - 0.9)	strong
[-1.0 - 1.0]	very strong

Figure 30 -Matrix of interaction for Piekary Śląskie

Within the boundaries of the city of Piekary Śląskie, the results of the analysis indicate that most of the correlation values in the matrix are lower than 0.3, indicating the absence of significant relationships between the analysed factors or insufficient data to carry out reliable calculations. This may suggest, among other things, that risk determinants do not have a direct impact on secondary risks or that there are other factors not included in the analysis that moderate these relationships. However, in several cases, clearer relationships were identified. The strongest relationship is between deformation and heap emissions, where the correlation is 0.88, indicating a strong relationship. This means that areas with intense rock mass movements may contribute to increased release of harmful substances from heaps. This may be the result of mechanical displacement of material stored on the heaps, which leads to increased emissions of dust and gases, especially as a result of erosion and degradation of the heap structure.

The results of the analysis for Piekary Śląskie indicate a moderate relationship (0.52) between land deformation and the risk of flooding. This means that in areas with intense rock mass movements, the probability of floodplains increases.

Wałbrzych

	hazards	determinants					
		radiation emission	sinkhole	mining induced floods	deformations	self combustion	environment pollution from spoils
secondary hazards	radiation emission	X	0,29	0,00	0,05	0,00	0,00
	sinkhole	0,00	X	0,21	0,33	0,08	0,00
	mining induced floods	0,00	0,21	X	0,41	0,00	0,00
	deformations	0,00	0,33	0,41	X	0,22	0,00
	self combustion	0,00	0,08	0,12	0,22	X	0,00
	environment pollution from spoils	0,00	0,21	0,00	0,04	0,03	X

correlation coefficient r	correlation
[-0.2 - 0.2]	very weak/negligible
(-0.4 - -0.2]+[0.2 - 0.4)	weak
(-0.7 - -0.4]+[0.4 - 0.7)	average
(-0.9 - -0.7]+[0.7 - 0.9)	strong
[-1.0 - 1.0]	very strong

Figure 31 -Matrix of interaction for Wałbrzych

Also, in the case of Wałbrzych, most of the relationships between determinants and secondary hazards do not show significant relationships. This may suggest that the determinants do not have a direct impact on the secondary hazards or that insufficient data was available to make viable determinations. Of all the relationships analysed, two show a moderate relationship. One of the key relationships is that between deformation and floodplains (0.41) (and the inverse relationship). It indicates that areas with intense rock mass movements are more prone to surface and groundwater accumulation, leading to flooding. This may be due to ground subsidence and changes in the natural drainage system that favour local water accumulation. Deformations can also affect the structure of aquifers, causing groundwater levels to rise and leading to flooding. Also, the mere presence of water and the degree of occupation of the land can cause secondary deformations due to land subsidence and changes in the water system and land retention.

Reasons for the different values of correlation between hazards in the analysed study areas.

Despite the application of a uniform methodology for risk assessment in the three analysed cities - Sosnowiec, Piekary Śląskie and Wałbrzych - the results of the correlation analysis between hazards show significant differences. This is not only due to the actual differences in the processes taking place in these regions, but also to a number of factors related to the scope of the study, the availability of data and the way in which it is obtained and compiled. One of the key aspects influencing the results is the scale of the research. If in one city mainly heavily degraded areas were analysed, while in another, areas less exposed to the effects of mining exploitation were also taken into account, the naturally obtained correlations between the different risk factors may differ. The greater detail of the data in a specific area may lead to a better capture of the interrelationships, whereas in broader analyses covering more diverse areas, the relationships may become weakened.

Data availability and quality are another important factor influencing the results of the analysis. In different cities, the availability of historical data and current measurements may vary, which has a direct impact on the precision of the correlations obtained. In one region, more detailed information may be available on, for example, radon emissions or land subsidence, while in another, the same hazards may be recorded less accurately or at greater intervals. Differences in measurement methods and frequency of data collection may result in strong correlations being detected in one city, while in another the same correlations are less clear or remain statistically insignificant.

The diversity of data sources is also important. If in one city the data is mainly from field measurements and in another it is largely based on numerical models or archival data, this can affect the interpretation of the results. Data from different sources may have different levels of accuracy and possible inaccuracies may cause discrepancies in correlations between hazards.

The temporal scope of the available data may also influence the results. If an analysis in one city covers a longer historical period, it may reveal more stable relationships between hazards that are not necessarily apparent in cities where only more recent or short-term data is available. For example, the impact of sinkholes on deformation may be more apparent in analyses covering decades of observation, while in short-term studies the relationship may go undetected.

The variation in results may also be influenced by the data processing methodology adopted. In some cases, the data may be analysed at a very detailed level (e.g. single measurement points), while in others it may be averaged over larger areas, which may result in smoothed relationships and weaker correlations.

5 Identification of elements at risks: buildings, infrastructures, etc.

The different elements at risks are described.

5.1 Road and rail infrastructure

Sosnowiec is a city that is well-connected in terms of both road and rail infrastructure. The several roads run through the city:4 national roads, 2 expressways, 2 uropean routes. Sosnowiec is also well-connected by rail, with four stations and one passenger stop serving domestic routes. Thanks to this, Sosnowiec is well-connected to the rest of the country and major cities, making it an important transport hub in the region.

Piekary Śląskie

Piekary Śląskie is well connected by both road and rail networks. The city is served by several important roads, including National Road No. 94 (connecting Zgorzelec, Wrocław, Katowice, Kraków), and Provincial Roads No. 911 and 913, linking Piekary with nearby towns and cities. The city also benefits from close proximity to the A1 motorway.

Piekary Śląskie doesn’t have rail infrastructure.

Wałbrzych

Wałbrzych is well connected to other cities through a network of national and regional roads. One national road is connecting city with Wrocław and the state border. Moreover 5 provincional roads are connecting the city with other towns in the area of Lower Silesia.

Wałbrzych is well connected by rail, with lines of supraregional importance. The city has four main railway stations. The main railway line connects Wrocław with Jelenia Góra and further to Jakuszyce and Görlitz.

5.2 Buildings

In Sosnowiec, Piekary Śląskie, and Wałbrzych, the urban structure is characterized by a mix of low-rise and multi-story buildings.

- Sosnowiec: Low-rise buildings, such as single-family and two-family houses, dominate the city, accounting for about 70-80% of the built-up area. Most of buildings are older than 50 years. Multi-story residential blocks make up around 20-30%. The population predominantly lives in low-rise buildings, but multi-story apartments are more common in central areas. The city has some historical buildings, especially in the city center, as well as modern structures using advanced building materials and complex shapes.
- Piekary Śląskie: Similar to Sosnowiec, low-rise buildings make up around 70-80% of the urban area, while multi-story apartment blocks represent about 20-30%. Most residents live in single-family homes, with a smaller portion in apartment buildings. Most of buildings are older than 55 years. Piekary Śląskie also features some historic buildings, particularly religious structures, and there are newer buildings with modern architectural styles.

- Wałbrzych: The majority of the city is composed of low-rise buildings, with single-family homes making up around 70-80% of the built-up area. Multi-story blocks account for about 20-30%, mainly in more urbanized zones. Most of buildings are older than 60 years. There are notable historic buildings, including former industrial architecture, and some modern buildings with innovative designs and materials, especially in newly developed areas.

In all three cities, low-rise housing is the most common, but multi-story apartment blocks are increasingly found in central and urbanized areas. There are also a mix of historical and modern architectural landmarks throughout these cities. The examples of damages to building's in Wałbrzych are presented on Figure 32.

Figure 32 -Damages to residential and historical buildings in Wałbrzych

5.3 Energy and Heating Networks in Sosnowiec, Piekary Śląskie, and Wałbrzych

- **Sosnowiec**: The city has a well-developed energy network, with electricity being supplied through the national grid. It is also connected to the central heating system, which is supplied mainly by local combined heat and power plants (CHP). Sosnowiec is part of the Silesian region's district heating network, providing heating to residential, commercial, and industrial buildings. The city is also increasingly investing in renewable energy sources to meet growing environmental standards.
- **Piekary Śląskie**: Piekary Śląskie is connected to the regional energy and heating infrastructure. The city receives electricity from the national grid, and district heating is widely available, particularly in residential areas. The heating network is supplied by local heating plants that provide thermal energy to many buildings in the city. As with other cities in the Silesian region, Piekary Śląskie is looking at expanding renewable energy sources to reduce emissions and improve sustainability.
- **Wałbrzych**: Wałbrzych is connected to a reliable energy network, with electricity provided through the national grid. The city has a comprehensive district heating system, supplied by local heat plants, including the Wałbrzych Heat Plant, which provides heating to a significant portion of the city. The city also benefits from combined heat and power systems that increase energy efficiency. Wałbrzych has also started to implement sustainable solutions,

such as biomass-based heating, and there are efforts to increase the use of renewable energy sources.

All three cities are connected to the national energy grid and have developed district heating systems that play a significant role in providing warmth to residents, with a growing emphasis on renewable energy and sustainability in line with regional goals.

In all the cities, urban infrastructure elements are exposed to factors such as subsidence (or uplifting) of the surface, the formation of floodplains in subsidence basins, and seismic activity induced by mining operations. Pictures on Figure 33 illustrates the damages to energetic infrastructure due to foodplains and subsidence. The elimination of damage caused by the destruction of buildings follows a brief description of the procedure outlined below. Gas, heating, and energy networks are monitored for potential displacements that could lead to leakage.

Figure 33 -Damages due to floodplains and subsidence - deviation from verticality (GIG's archives)

In Poland Coal Mining Companies, individual divisions (coal mines) are responsible for financial compensation of repairs of buildings damages due to induced seismicity hazard.

All mines have uniform rules and procedures for dealing with mining damage, as defined by internal regulations, in particular:

- Instruction on the procedure and principles of proceeding in removing and preventing damage caused by the mining plant's motion,
- Procedure for dealing with mining damage as part of the ISO integrated management system,
- Notification of damage.

The scheme of actions and decision making

- Immediately after the occurrence of a tremor, the technical services of the mine determine the range of vibration effects of the individual degrees of intensity on the GSIS-2017 scale**.** In the case of receiving a report on the occurrence of damage to a building, if the building is within the range of vibrations of an intensity greater than I on the GSIS-2017 scale, a visual inspection of the structure is mandatory.

- In the event of a mining induced tremor with vibration parameters corresponding to degree IV on the GSIS-2017 scale or higher, all buildings within the range of these degrees of intensity shall be inspected, irrespective of whether a report of damage to them has been received. In justified cases, expert opinions must also be carried out on the load-bearing structures and bracing elements of the buildings.
- The inspection of the damage reported after the shock is carried out in the following order:
    - Firstly: the inspection is carried out on buildings in which damage is reported that threatens the safety of their use (in the opinion of the notifier),
    - Secondly: the remaining damaged buildings, starting with those in the zone with the highest degree of vibration intensity.
- The basis for assessing the cause-and-effect relationship between the movement of the mine and the reported damage, in each case, is an analysis of the parameters and the extent of the impact of the shock, based, among other things, on the vibration recordings made at the surface measuring stations.
- Each mine provides a 24/7 facility for receiving reports of the effects of shaking on the surface. The telephone numbers for reporting the effects of a tremor can be found under "Shock Notification" on the website of each mine.
- The costs of repairing damage to buildings shall be paid by the coal mine.

6 Identification of Vulnerability factors

Vulnerability is a pivotal element in multi-risk analysis, signifying the extent to which specific elements at risk (EAR) such as persons, structures, and infrastructures are susceptible to risk. It incorporates a multitude of factors, including demographics, infrastructure, socio-economic conditions, and community resilience. For the POMHAZ project, a specific post-mining Vulnerability Index (VI) was developed in WP3. It is calculated from 4 weighted classes with 10 subclasses:

- Socioeconomic status (Unemployment rate, GDP per capita),
- Household composition (Population < 15 y.o. / > 64 y.o., population density),
- Environment (Settlement area, agricultural area),
- Infrastructure (Building ag, material, geometry and traffic area).

After normalization of each subclass from 1 to 9 and calculating the average for each class, the vulnerability index (VI) can be calculated for each zone (e.g. municipality) and then rasterized. The standard weights are 0,3 for socioeconomic status, 0,4 for household composition, 0,1 for environment and 0,2 for infrastructure.

For the cases of Sosnowiec, Piekary Śląskie and Wałbrzych the analysis was done by GIG using local data sources. The data 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 2 shows the values for the three cities in the AOI. Publicly available data from sources such as the Statistics Poland (Central Statistical Office), Geoportal PL, www.geoportal.gov.pl (layers relating to environmental, socioeconomic and technical aspects - infrastructure of selected areas) were used for the calculation of VI.

Table 2 - The VI calculation of the three cities in the test case, compared to the world, EU and Poland average

City	Socioeconomic factor	Household factor	Environmental factor	Infrastructure factor	Vulnerability Index (VI)
Sosnowiec	6	7	5	4	5,9
Piekary Śląskie	7,5	6	5	3,75	5,9
Wałbrzych	5,5	6,5	4	4,1	5,47
Poland average	6	3,5	4	3,25	4,25
EU average	4,5	3	2,5	3,875	3,575
World average	6	2,5	2,5	4	3,85

The analysis shows that the VI index of the former mining regions is well higher than the Polish and EU average, indicating a higher vulnerability to post-mining hazards. This is mainly due to somewhat worse socio-economic, household and environmental factors, all of which can be linked to the closure of mines. Although the unemployment rate is not significantly higher, the GDP per capita in these cities is comparatively low, resulting in a moderately higher socio-economic vulnerability."A high population density and a high percentage of the population in the non-working age group (< 15 years or > 64 years) push the household vulnerability factor far above the average. The high percentage of settlement area negatively affects the environment factor. The infrastructure factor is quite average, as the age, materials and geometries of the buildings are not unusual.

7 Available data

The data collected and prepared according to the requirements were presented in form of differents maps and visualisations. The data was prepared in the form of a QGIS project, containing vector data layers in *.shp format.

The most important prepared concerned mining issues:

- Seam maps
- Shafts, shafts and headings connected to the Surface
- Seams
- Shallow mining
- Protective pillars
- Waste dumps and Settling ponds,
- Deformation and Faults
- Adits
- Occurences/outcrops of various geological formations,
- Depressions from the beginning to 1996
- Subsidences 1946 to 1996
- Age-related subsidences
- Reservoirs - extent of underground water bodies
- Overflow lands - areas of projected potential flooding
- Study areas - area of possible anomalous radon and other gases concentrations.

Some of the data came from old archival collections – for example map presented on Figure 34 – and has local coordinate reference system. Therefore, old reference system had to be converted, using Helmert transformation to the current EPSG:2180 CS92 system.

We have used all available data sources, including publicly accessible resources. A significant portion of the data came from the GIG-PIB databases and archival resources of the State Mining Authority. Some data was collected from Polish Geological Institute – National Research Institute. The municipal offices of partner cities were helpful in gathering the data. We also used data from publicly available state resources: geoportal.gov.pl.

Figure 34 - An example of old maps, used in the preparation process

8 Application of the case study using DSS-GIS tool

An essential aspect of risk assessment is understanding how multiple factors interact over a broad spatial scale. By implementing the previous WPs of the project, knowledge was accumulated and methodologies developed, which formed the basis for the application of the DSS-GIS tool in case studies. Within WP2 "Post mining hazards and multi hazard identification and assessment methodology", the partners built a database of hazards related to closed and abandoned mines (T1.1., D1.1). Methodologies for post-mining hazards interactions were developed (T1.3, D1.3). While implementing WP3 "Post-mining risk assessment methodology and decision support system", the partners developed the activities described above, prepared guidelines and recommendations. In task T3.1, the partners analysed interactions between hazards (especially subsidence and others), created interaction matrices. Deliverable D3.1 presents the three key factors typically used to calculate multi-risk (Dalezios, 2017) associated with post-mining in each of the study areas: post-mining multi-hazard interaction, exposed elements at risk, and vulnerability. The DSS-GIS tool, designed in task 3.2 and developed as a web application programming interface (API) in task T3.3, serves as a comprehensive solution for integrating all factors into a multihazard map. These results were presented in the deliverables D3.2 and D3.3. In addition, the DSS-GIS tool provides experts and authorities with the flexibility to adopt different risk management approaches based on specific needs, such as environmental impact assessment, structural damage mitigation, or other relevant concerns (e.g. groundwater contamination, land subsidence).

Based on discussions with specialists from the cities, GIG, and SRK, as well as methodologies reviewed during POMHAZ meetings, the tool was evaluated for different risk scenarios in the post-mining areas of Sosnowiec, Piekary Śląskie, and Wałbrzych, all of which have a history of coal mining.

The geospatial data for the study areas were integrated into the DSS system using a PostGIS database. The system is designed to process user requests via the API and allows the development of different scenarios to suit the needs of the expert. In this report, two scenarios are presented for each study area. The analysis calculates the Multi-Risk Index within the district boundaries of each city, providing authorities a clearer visualization of the impact of post-mining events on their communities.

In each site the interaction between the following post-mining hazards can be evaluated:

- Sinkholes,
- Subsidence,
- Ionizing radiation emissions,
- Combustion and overheating,
- Mine water,
- Mining-induced flood,
- and environmental water polution.

Based on the results in Table 1 and the interaction matrix in Figure 28, the hazard weightings in the API were established according to their level of importance within the scenario and their interactions with other hazards.

POMHAZ allowing to calculate the Multi-Hazard Index (MHI) for a given scenario using an adapted principal method that considers three levels of hazard interaction:

- Low or no interaction – The initial hazard remains unchanged.
- Medium interaction – The initial hazard intensity increases by at least one level.

- High interaction – The intensity increase depends on the initial level, ranging from one to two levels.

Additionally, the adjusted principle adopted in this project accounts for the number of interactions each hazard has with others at different interaction levels. Finally, the MHI is normalized on a scale from 1 to 9, where 1 represents no hazard or no risk, and 9 indicates a very high-risk location.

For comparison, in one scenario, the relationship between subsidence, sinkholes and mining-induced flooding will be evaluated to assess ground movement events in the study areas of Sosnowiec, Piekary Śląskie and Wałbrzych. In the case of Sosnowiec, an additional scenario is considered that includes all mining-related hazards present in the area.

8.1 Case 1 – Sosnowiec

The first step in calculating the Multi-Hazard Index (see chapter 5) in the API is to select the hazards to analyze. The platform allows the user to define both the level of interaction and the number of interactions by positioning the hazards accordingly. As shown in Figure 35, in the first scenario, subsidence and sinkholes have a high level of interaction with mining-induced flooding, while flooding has a medium level of interaction compared to the other two hazards, as noted in Figure 28. However, flooding is centrally located, giving it greater weight in terms of the number of interactions that exist. For the second scenario, a cascade effect can be observed where sinkhole formation acts as a trigger for four other hazards. Sinkholes can accelerate water infiltration, leading to increased subsidence and flooding. They can also disturb radioactive materials, increasing the risk of radiation exposure. In addition, sinkholes can serve as direct pathways for contaminants, exacerbating water pollution. Finally, if they occur near combustible mine waste, they can increase air and water pollution and accelerate oxidation and combustion. As in the first scenario, subsidence is highly interactive with mining-induced flooding. However, since subsidence can occur in any post-mining environment, it can also contribute to the same mining-related hazards caused by sinkholes.

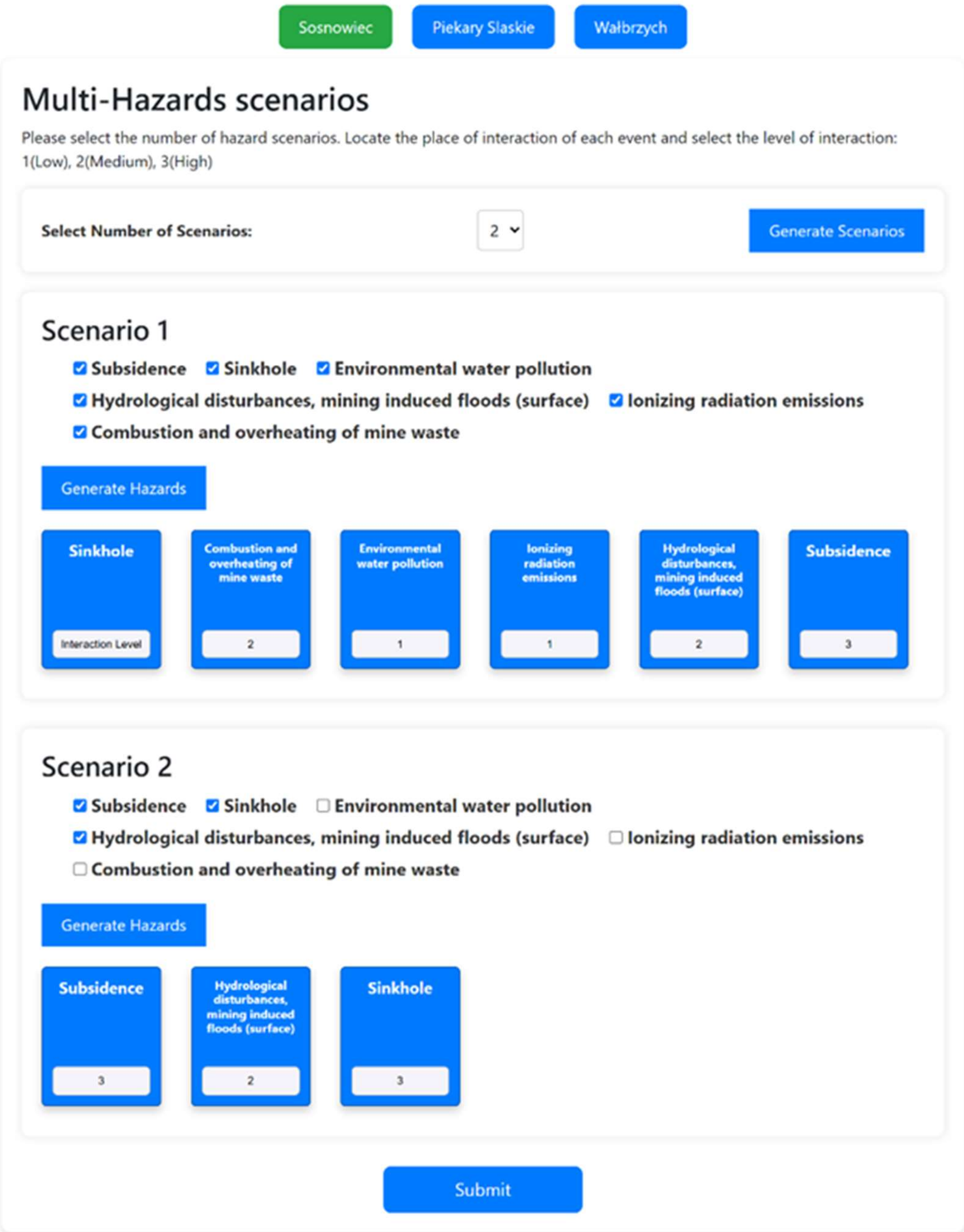


Figure 35 - MHI selection in the API for multi-hazards scenarios in Sosnowiec

The weighting calculation for each scenario is performed on the API server, which retrieves all relevant hazards from the PostGIS database and returns the results as a raster file with a resolution of 10m. The hazard map for the Sosnowiec case is shown in Figure 36, which shows the results for both scenarios. Users can also download the data as a .tif file for further analysis in other geospatial software. In addition, if the results are unsatisfactory or a different type of assessment is required, users can reset the MHI selection and redefine the scenario parameters.

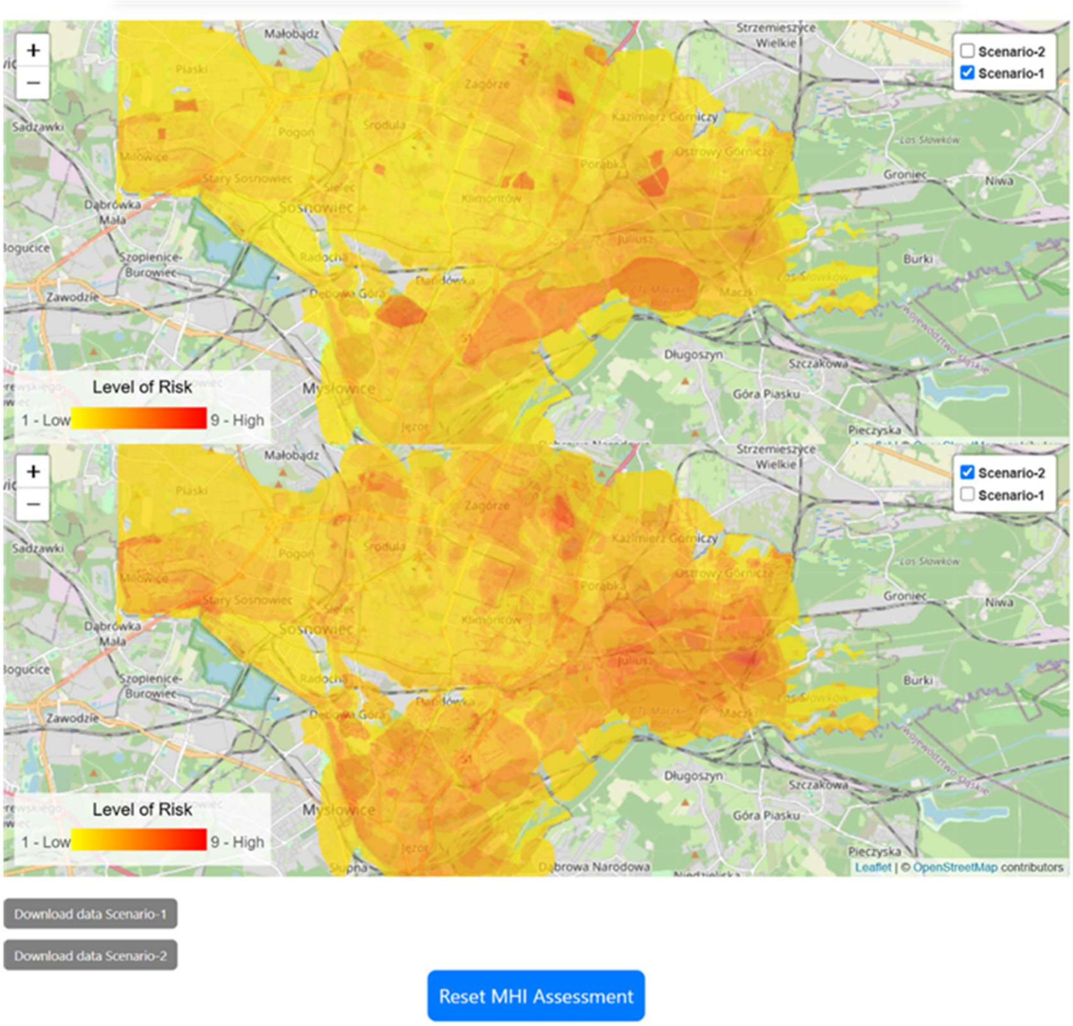


Figure 36 -MHI risk map for Sosnowiec case. (Top) Scenario-1 with all involving hazards in the area. (Bottom) Scenario-2 with only Sinkhole, Subsidence and mining-induced flooding

The second risk factor to assess is the Exposed Elements at Risk (see chapter 6). To ensure consistency across case studies, Land Use/Land Cover (LULC) data derived from Sentinel-2 imagery was utilized (Esri, 2024). The expert user is required to assign a risk level, ranging from 1 to 9, to each classification. For the exemplary case, the matrix presented in Figure 37, based on insights from THGA experts, will be applied to the different classes of the LULC reclassification. As shown, building areas are assigned the highest level of significance, while Snow/Ice classes are given the lowest significance based on their relevance. This matrix will be used in all three cases.

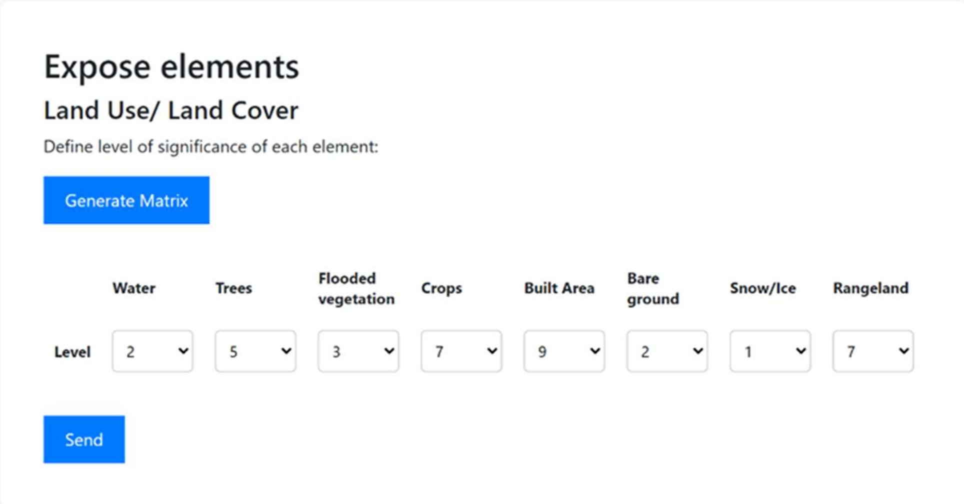


Figure 37 -Exposed element at Risk matrix used for study cases

The response of the EAR is then sent to the backend, where the reclassification of the LULC data is performed based on the assigned importance levels of each class. The results, reflecting the reclassified LULC data for the Sosnowiec case, are shown in Figure 38. As shown, the expert can evaluate the different classes and obtain a more precise identification of the location for each class. Also as with the MHI results, the data could be downloaded in a raster file for further evaluation.

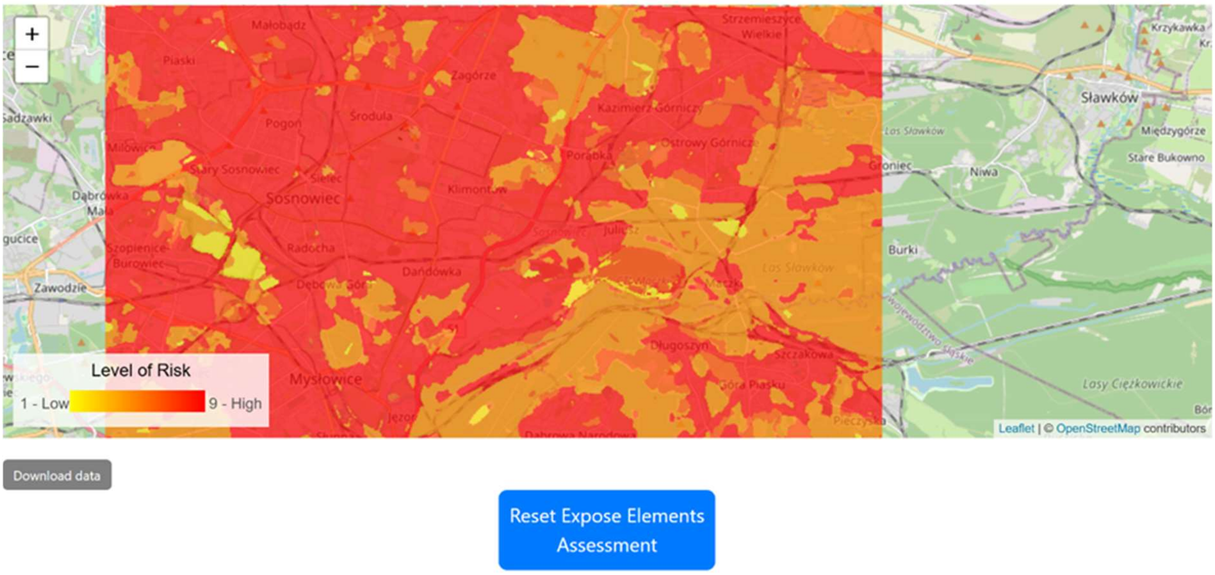


Figure 38 - Map of EAR for Sosnowiec study case

The third element to be evaluated is the Vulnerability Index (VI) for each location (see chapter 7). The API incorporates data from the database on the following vulnerability indicators for all cities in the study area, as well as national values for comparison: Socioeconomic Status, Household Composition, Environment, and Infrastructure. The weighting results are based on the sub-classes selected for each category.

Socioeconomic status is evaluated using indicators like unemployment rate and gross domestic product (GDP).

Household composition is assessed based on the population under 18 years, over 64 years, and population density for each city.

Environmental factors consider the extent of settlement and agricultural areas.

Infrastructure is classified according to building characteristics (such as age, materials, and geometry) and traffic areas.

Experts can then rate the importance of each category on a scale from 0.1 (less important) to 1 (very important), with the sum of the weights adding up to 1. The matrix shown in Figure 39 is applied to all study cases, with particular emphasis on the household composition and socioeconomic status indicators.

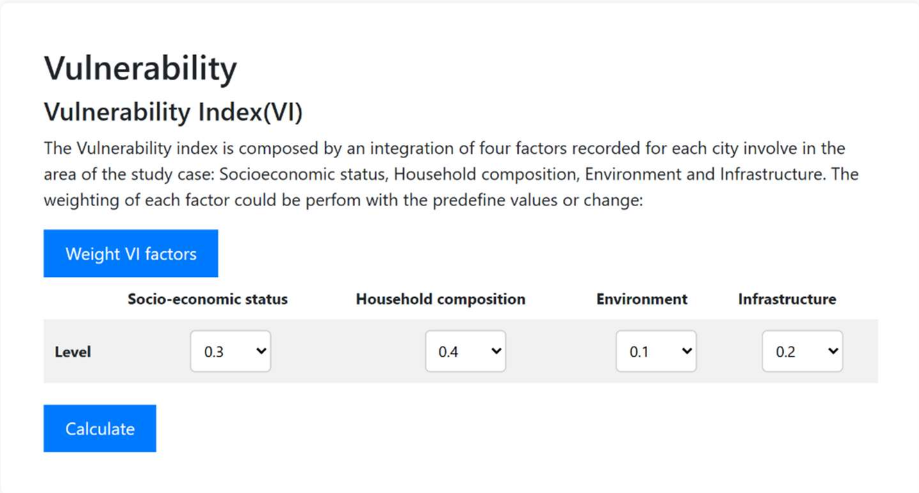


Figure 39 -Matrix for calculation of Vulnerability Index

Figure 40 shows the results of the Vulnerability Index (VI) map for Sosnowiec, along with maps for each individual class. As seen, the expert can view not only the data for Sosnowiec but also for the “Rest of Poland,” which includes national-level information. Additionally, the vulnerability map containing all case data is available for download in either GeoJSON or Shapefile format.

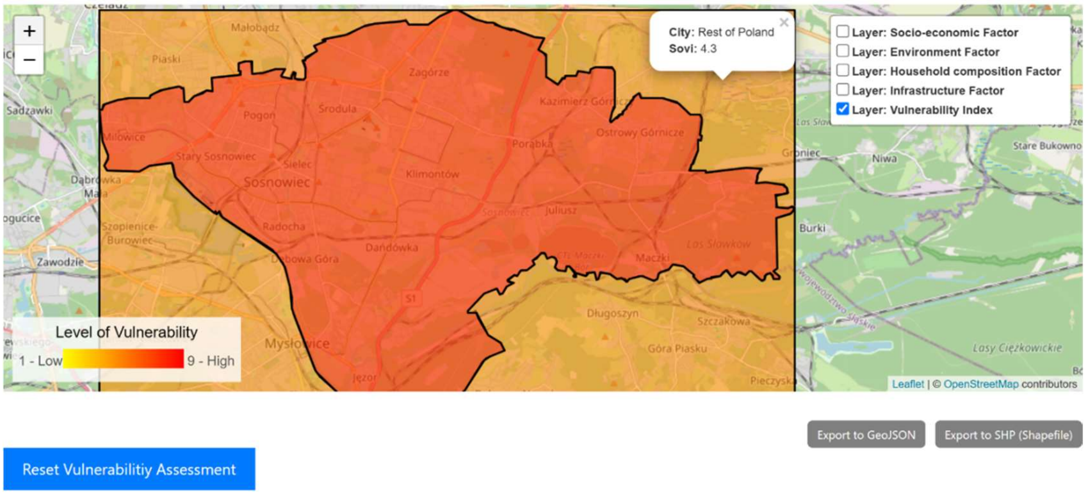


Figure 40 -Vulnerability Index map for Sosnowiec case

After calculating all three factors, the API stores the results in the database. In the final component, these results are aggregated into a Multi-Risk Map. Depending on the selected scenarios, one or multiple layers will be displayed. The map includes all multi-risk values, allowing experts to define the low, medium, and high-risk areas using a slider. The POMHAZ API also provides recommendations for each of the three risk levels. For low-risk areas, monitoring is suggested; for medium-risk areas, mitigation techniques should be applied; and for high-risk areas, a land repurposing strategy is recommended. This information can be viewed directly on the web or downloaded as a PDF file. Figure 41 presents the results of the Multi-Risk Map for the Sosnowiec case across both multi-hazard scenarios.

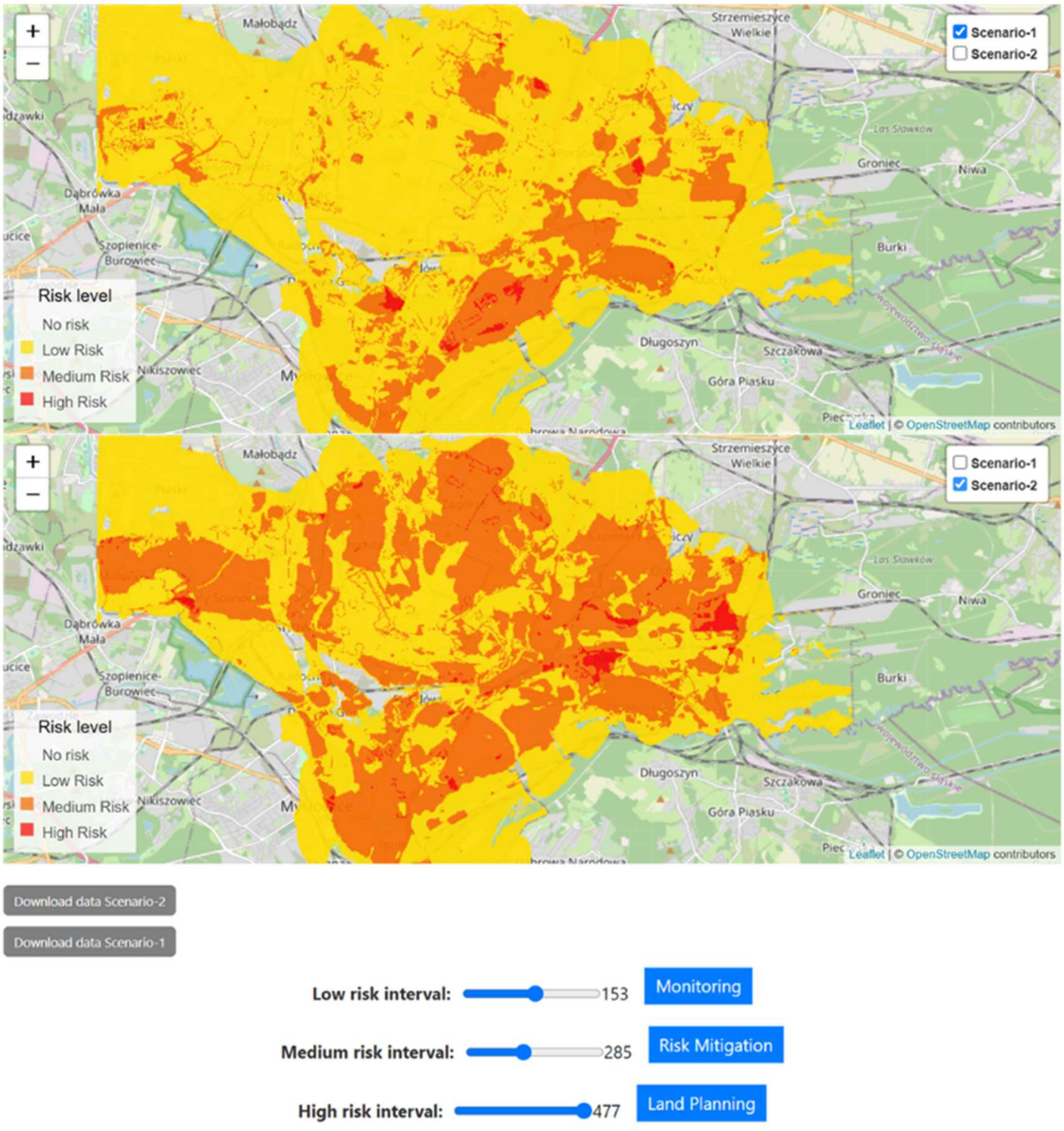


Figure 41 -Multi-risk map of Sosnowiec study case. (Top) Scenario-1 with all hazards involved. (Bottom) Scenario-2 Risk map with Sinkhole, Subsidence and induced mining flooding

For further evaluation, the API presents the risk scenario results through interactive dashboards (Figure 42). Users can analyze each risk class defined in the map, identifying areas with higher or lower risk levels. The dashboard also provides a summary of the hazards used in the analysis and displays the geographic coordinates of any selected point. Additionally, the dashboard allows users to integrate extra geospatial layers for further analysis. In the example shown in Figure 42, a layer displaying schools in Sosnowiec (Humanitarian OpenStreetMap Team, 2024) was added. This enables users to define a risk polygon and assess the number of schools potentially exposed to multi-hazard risks.

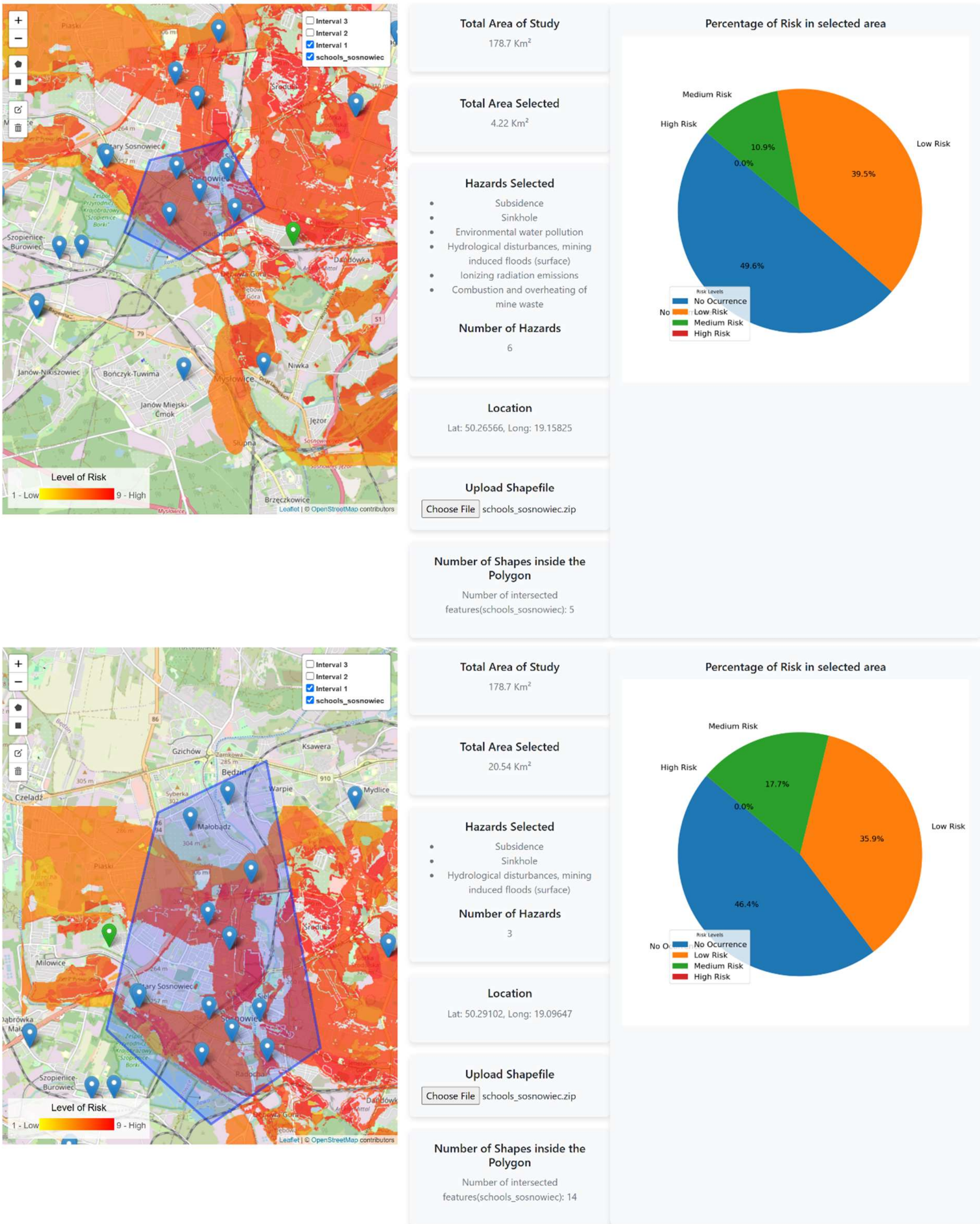
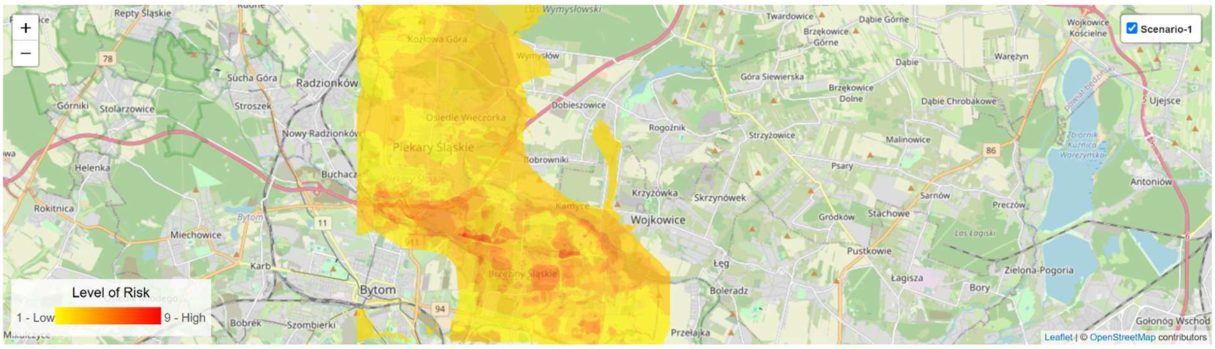


Figure 42 -(Top) Dashboard of Scenario-1 of Sosnowiec case for Low-Risk interval. (Bottom) Dashboard of Scenario-2 of Sosnowiec case for Low-Risk interval

8.2 Case 2 – Piekary Śląskie

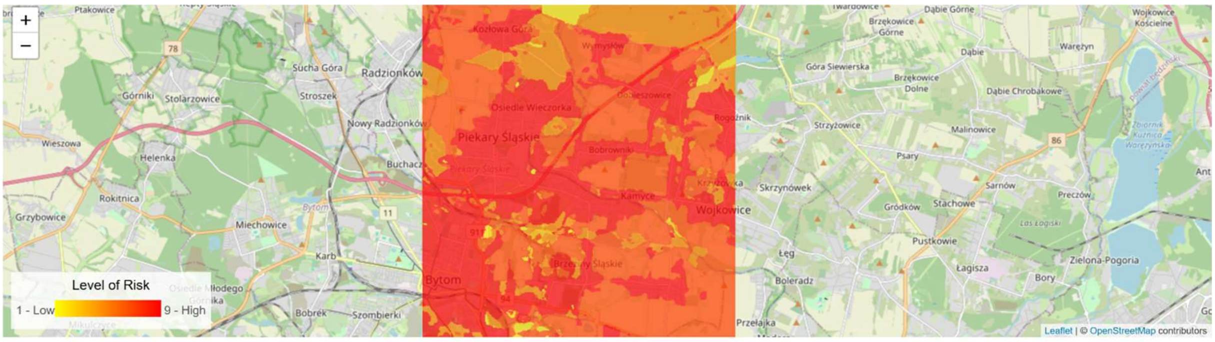
For Piekary Śląskie, a single scenario incorporating all available hazards in the area is presented. The MHI results, generated using the DSS API, are shown in Figure 43. Similar to the Sosnowiec case, greater interaction levels will be assigned to sinkhole and subsidence hazards, as they have the potential to trigger other post-mining events.



Download data Scenario-1

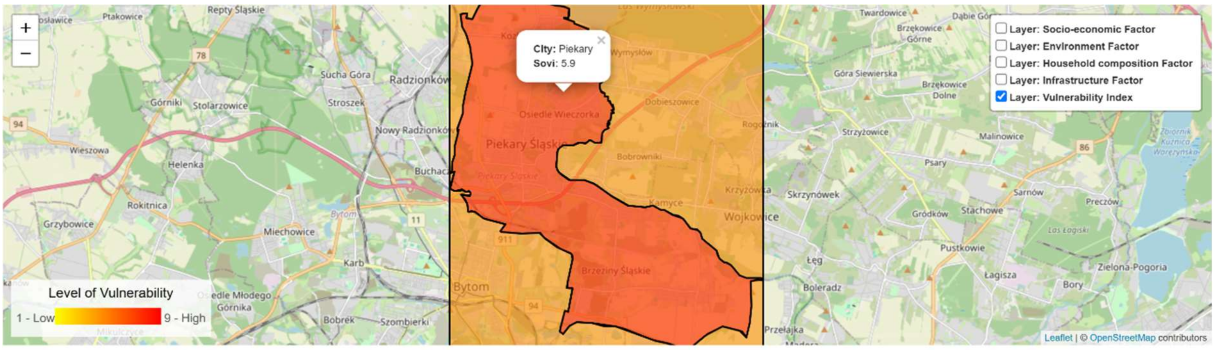
Figure 43 -MHI hazard map for Piekary Śląskie case with all involving post-mining hazards in the area

Figure 44 and Figure 45 present the results for exposed elements at risk and the vulnerability factor, respectively. The LU/LC layer (Esri, 2024) indicates that approximately 70% of the area is classified as Built Area and Crops, with priority given to Built Area in this analysis. For the vulnerability factor, household composition was assigned a higher weight. The final vulnerability index for Piekary Śląskie was 5.9, on a scale from 1 (low vulnerability) to 9 (high vulnerability).



Download data

Figure 44-Map of Exposed elements at Risk for Piekary Śląskie study case



Export to GeoJSON Export to SHP (Shapefile)

Figure 45 -Vulnerability Index map for Piekary Śląskie case

Finally, Figure 46 displays the results of the accumulation of the three risk factors in the API server, leading to the Multi-Risk Map for the Piekary Śląskie case on the platform. For illustrative purposes, risk intervals have been defined, as shown in the image, with each interval corresponding to a recommended risk management technique.

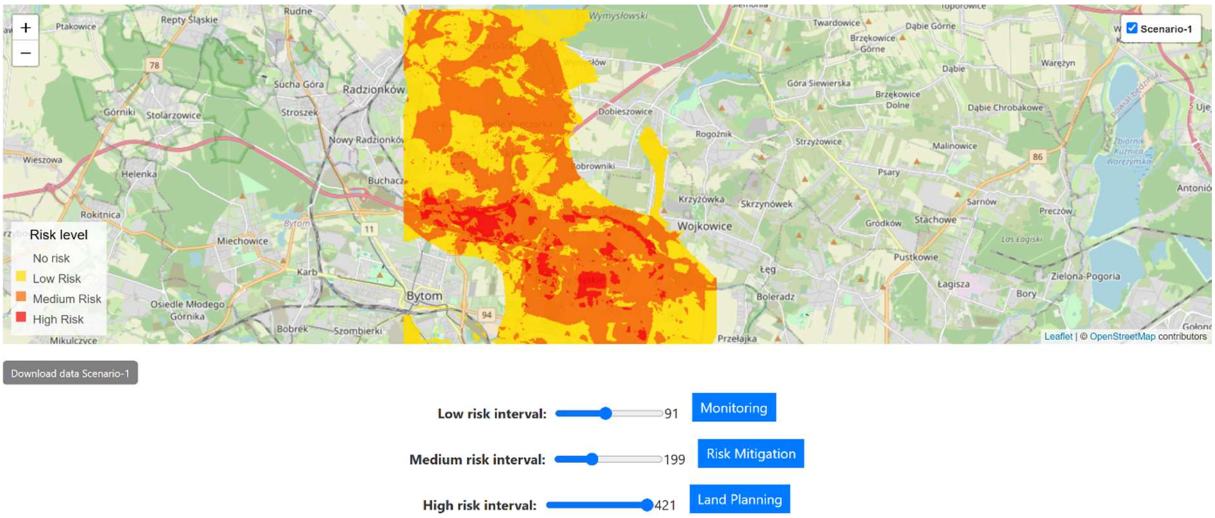


Figure 46 -Multi-risk map of Piekary Śląskie study case

The dynamic dashboard for the multi-risk scenario of Piekary Śląskie is shown in Figure 47. Similar to the Sosnowiec case, experts can visualize each risk interval separately and conduct further analysis. For this case, building footprint information (Humanitarian OpenStreetMap Team, 2024) is used to demonstrate one of the analyses possible with the database, highlighting the number of buildings exposed to risk and their locations.

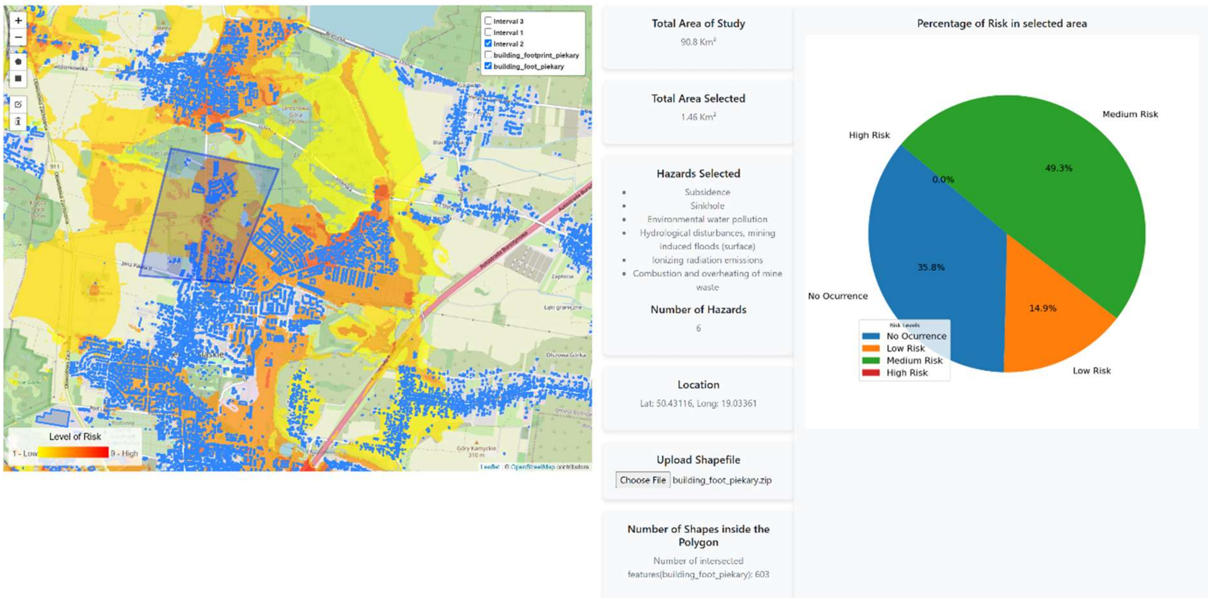
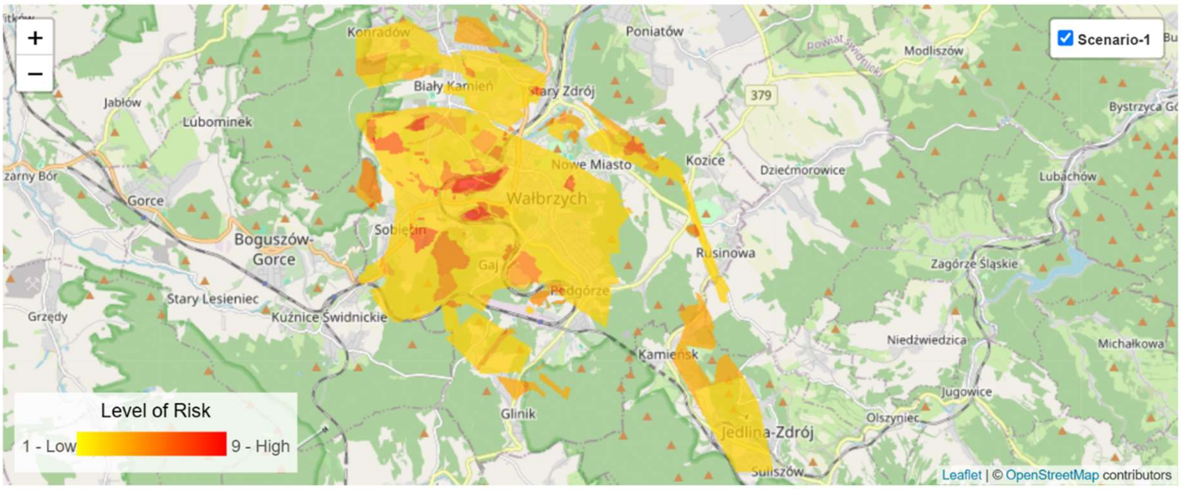


Figure 47 -Dashboard of Piekary Śląskie case for Low-Risk interval

8.3 Case 3 – Wałbrzych

In the final case, for the city of Wałbrzych, all the post-mining hazards available in the area are considered, similar to the Piekary Śląskie case. Greater interaction is assigned to subsidence and sinkhole hazards, which have the potential to trigger other post-mining events. Mining-induced flooding is also given a medium interaction level with both sinkhole and subsidence, as indicated in the risk matrix in Figure 31. The results of the MHI map are shown in Figure 48, reflecting the all-hazards interactions.



Download data Scenario-1

Figure 48 -MHI risk map for Piekary Śląskie case with all involving post-mining hazards in the area.

The results of the exposed elements at risk and vulnerability factor are shown in Figure 49 and Figure 50 respectevely. The DSS API calculates the reclassification of the LU/LC layer with giving high weighting to building areas, crops and range land and it is also showcased in Figure 49. For the vulnerability factor, the indicator with more weight was household composition in the same way of Piekary Slakie. The experts could see the spatial impact of both factors using just the DSS-GIS API.

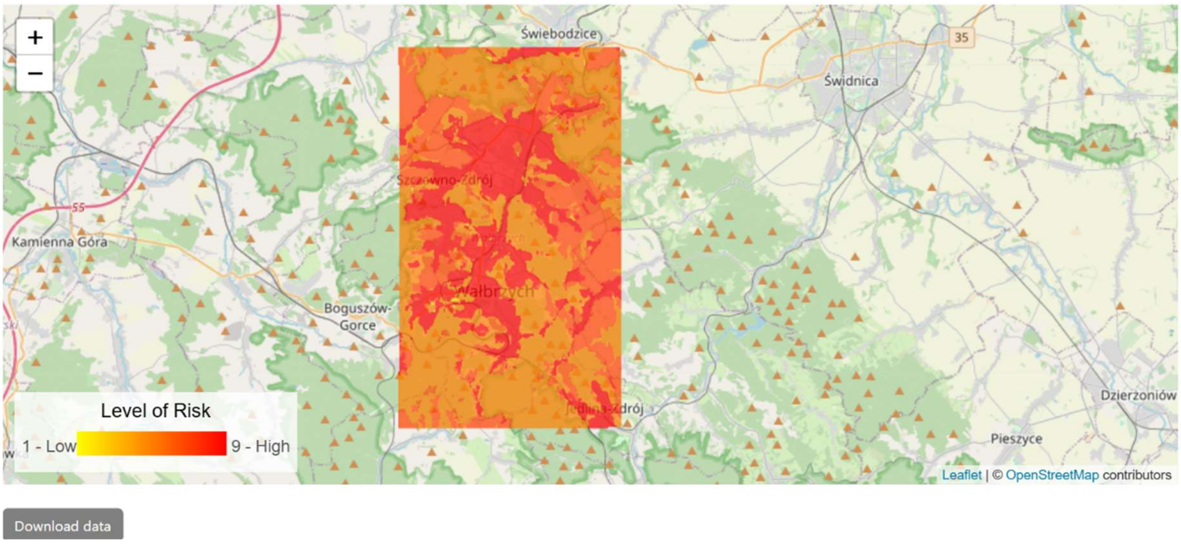


Figure 49 -Map of Exposed elements at Risk for Wałbrzych study case

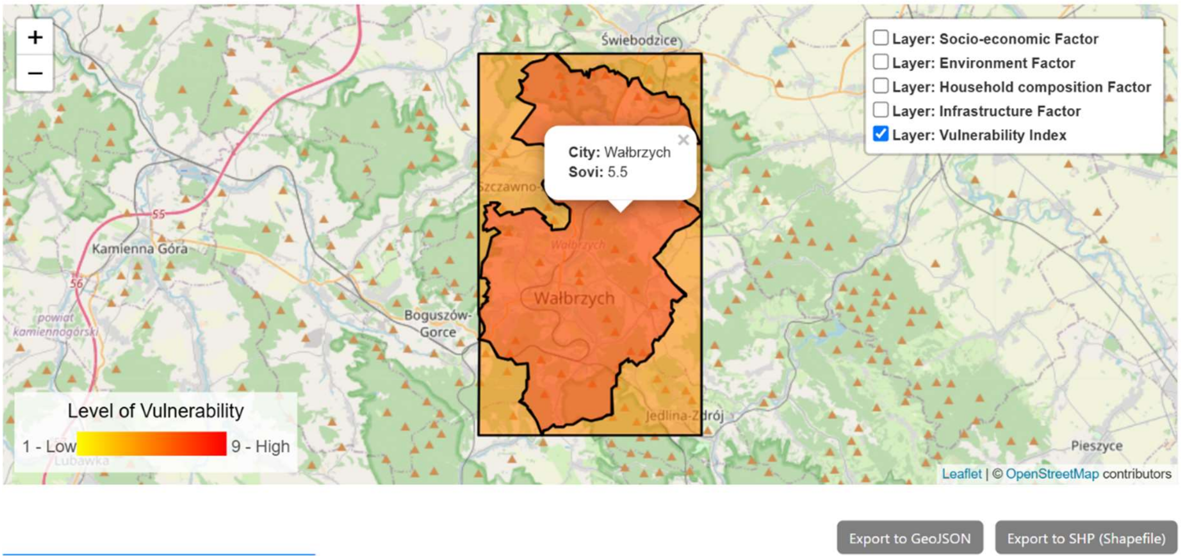


Figure 50 -Vulnerability Index map for Wałbrzych case

Lastly, the calculation of the Multi-Risk Index is presented in the map shown in Figure 51. The DSS API highlights several high-risk areas in the center of the city, demonstrating how the DSS-GIS tool can integrate multi-risk scenarios and assist experts in determining appropriate management techniques.

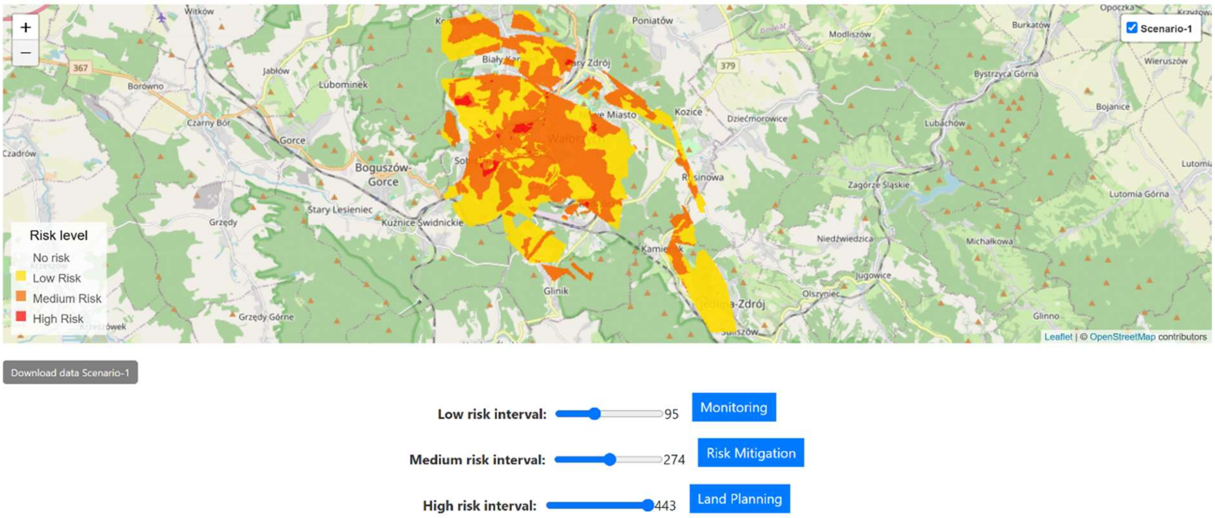


Figure 51 -Multi-risk map of Wałbrzych study case with all hazards involved

For further analysis, the dynamic dashboard displaying the multi-risk map intervals is shown in Figure 52. This dashboard also includes the building footprint data for the area, allowing users to visualize the number and specific buildings exposed to high-risk zones. Additionally, experts can view the overall risk classes for the selected area.

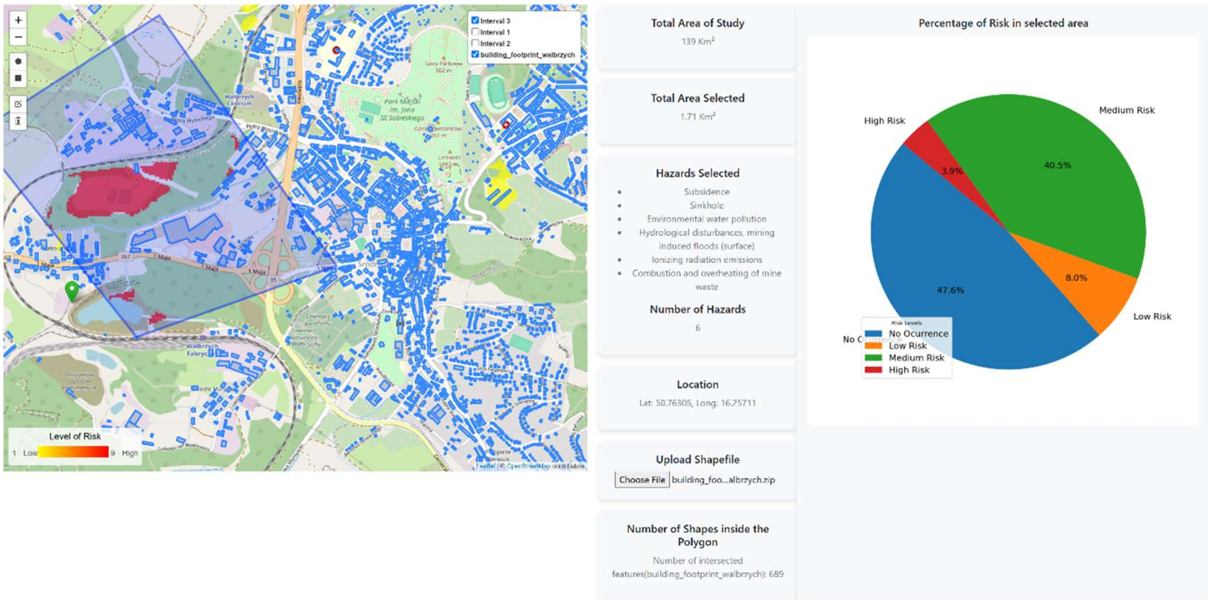


Figure 52 - Dashboard of Wałbrzych case for High-Risk interval

9 Conclusion

In Europe, coal mines have been gradually closing for several decades. In Poland, about 20 mines are still in operation. In the middle of the last century, there were almost 60 mines operating. Therefore, the impact of mining, the risks for the population and the environment are caused by the historical effects of mineral extraction as well as the contemporary effects of the closure of further mines.

Coal mining historically developed in Poland in two basins: the Lower Silesian and the Upper Silesian. The geological conditions and consequently the mining and technological solutions in the two centres differed. The last mine in the Lower Silesian district was closed in 1988, while coal is still being mined in Upper Silesia.

The deliverable presents the work done in the frame of the WP4, Task 4.4, to validate the application of the DSS-GIS tool for assessing the post-mining risk in coal region. Three Polish cities were identified for this work.

The selected case studies, i.e. the cities of Wałbrzych in Lower Silesia and Sosnowiec and Piekary Śląskie in Upper Silesia, are good testing grounds for observing the development of hazards, risks and their interaction. The collected hazard-specific databases provided good material for verification, validation and testing of the GIS -Decision Support System tool.

Each of the case studies has its own individual characteristics and conditions, determining the development of hazards and the intensity of their impacts.

The results of the analyses for the cities of Sosnowiec and Piekary Śląskie may be less precise than the analysis done for Wałbrzych. In Wałbrzych, where the mines were closed more than 20 years ago, the process of flooding the mines and stabilising the hydrostatic pressure is over. In Sosnowiec and Piekary Śląskie, the mines have been liquidated in recent years. Other mines are still operating in the vicinity of the closed mines. Therefore, the process of restoring the water table and stabilising the hydrostatic pressure is still ongoing. In addition, we do not know the exact scenarios for the total liquidation of the mining industry, for example how the dewaterig of mines will proceed, for how many years, etc. It can therefore be assumed that the correct implementation of the GIS-DSS tool in these cities confirms the system developers' assumption that the tool can be used throughout Europe.

In the system uniform data formats, compatible with the software are used. Historical data, in digital form or in other records, was standardised and converted to shapefile and rasterfile formats. The developed system analyses and visualises the information prepared according to the imposed standard. This makes it possible to assume that multi-risk analyses carried out with the support of a GIS-DSS tool anywhere in Europe will be comparable. This will certainly allow the development of coherent and standardised instructions and guidelines for the administration of post-mining municipalities throughout Europe in the future. Stakeholders such as developers, industrial partners and others will be able to use a single, universal tool to assess the advantages and disadvantages of planned investments.

Of course, it is necessary to be aware of the margin of uncertainty of the results obtained. The results of the hazard interaction study presented in the document showed that theoretical analyses depend on the quality of the data collected. One of the key aspects influencing the results of analyses is the scale of the research. The greater detail of the data in a specific area may lead to a better capture of the interrelationships, whereas in broader analyses covering more diverse areas, the relationships may become weakened. Data availability and quality is another important factor influencing the results of the analysis. The diversity of data sources is also important as well as the temporal scope of the available data.

It is also important to know that different post-mining areas have different vulnerabilities, depending on many specific factors. In our project the factors were divided into groups: socioeconomic status, hausehold composition, environment, infrastructure. Information and data were collected for each city, which served as the basis for calculating the so-called Vulnerability Index. In the document we presented examples of calculations of the index for different case studies.

The problem discussed above shows that expert knowledge and the ability to critically assess both the scope and quality of the data to be analysed and the resulting visualisations, models etc. are always necessary. The task to be carried out within the framework of the PoMHaz project to organise and conduct workshops with stakeholders will contribute to the future training of post-mine areas managers. The conclusions of the workshops will indicate areas for improvement for both professionals and supporting tools.

In the end, the analysis and visualisation of the risk of hazards will help local administrations to make decisions regarding the future development of post-mining areas. It will assist in presenting difficult situations and scenarios to both developers and residents in areas at risk.

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11 Annexes

List of annexes:

- Annex 1: Description of hazards, Upper Silesian Coal Basin Poland

Annex 1: Description of hazards, Upper Silesian Coal Basin Poland

1 Description of hazard, examles of previous post-mining measures

In Poland, mines have been liquidated for more than 20 years. During this time, various measures have been taken to limit the hazards and risks to the environment and inhabitants of post-mining areas. The critical analysis of existing tools and methodologies were performed within WP2 Post mining hazards and multi hazard identification and assessment methodology, Task 2.2.

Discontinuous deformations

The risk of sinkholes and ground subsidence exists in areas where coal mining was carried out in the outcrop coal beds add/or in areas of shallow exploitation. There were hundreds of shafts, pits and adits connected to the surface in Upper Silesia. Sinkholes can also form in these areas. This is why the shafts are backfilled in, closed off with concrete covers. Other connections to the surface (pits, adits etc.) are also generally backfilled.

GIG -PIB collects data on sinkholes occurring in the Upper Silesia area. At www *zapadliska.gig.eu*, a continuously updated map of sinkholes is available. Below are presented excerpts from maps showing the sinkholes in Sosnowiec and Piekary Śląskie (Figure 1 and 2).

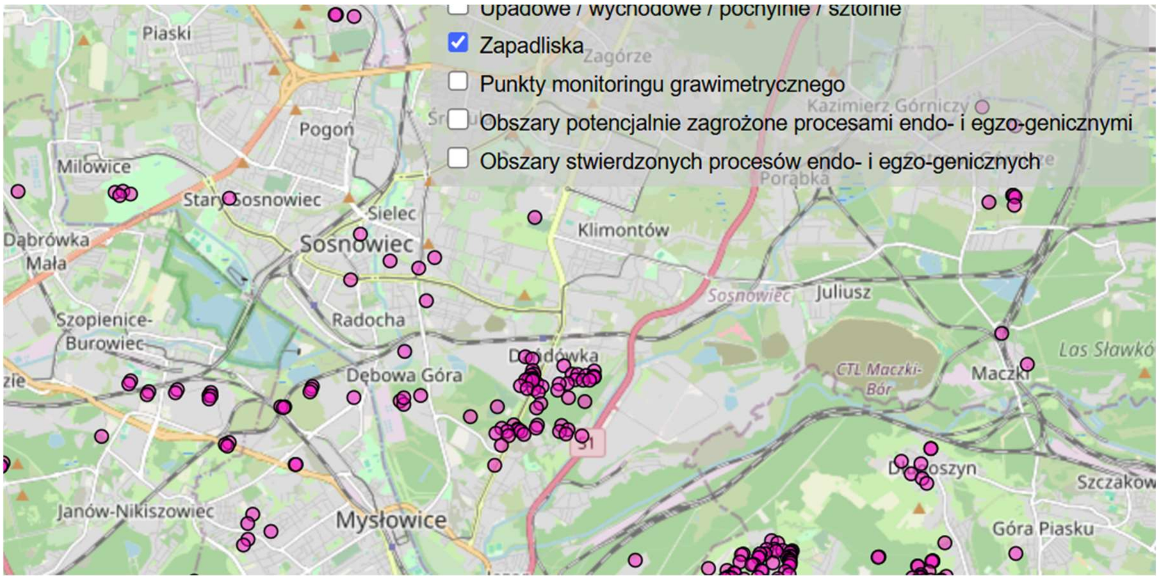

Figure 53 - The excerpt from the map of sinkholes in Sosnowiec
https://zapadliska.gig.eu/pl/content/mapa

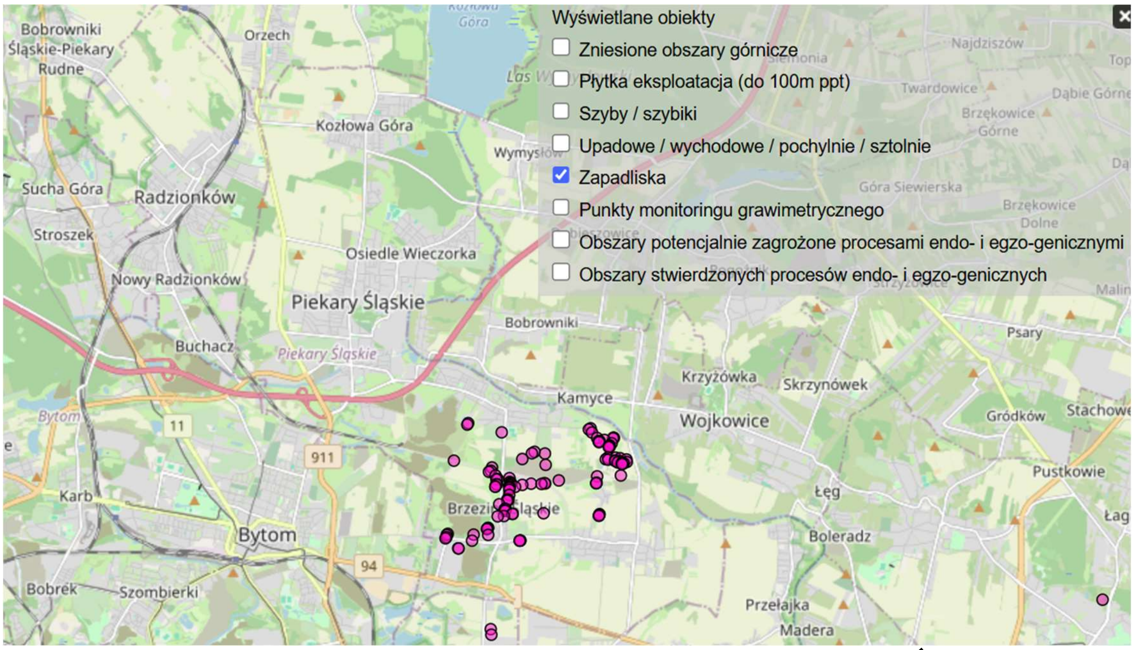

Figure 54 - The excerpt from the map of sinkholes in Piekary Śląskie
https://zapadliska.gig.eu/pl/content/mapa

Subsidence

The phenomenon of subsidence can occur in any post-mining area. The probability of formation depends on a number of factors: - intensity and duration of mining activities (past and temporary); - depth of mining activities (past and temporary); - extracted seems thickness; - geological structure of the rock mass; - tectonic disturbances (faults); - rock mass flooding; - period of time after the end of operation.

In Poland the method of the assessment of the risk of subsidence in post-mining areas for structures and infrastructures, is based on the values of strain and tilt. This method is not part of any legal act, it only supports professionals in the process of assessing the environmental conditions and making decisions.

In the proposal there are 3 degrees of consequences (minor, major, severe) depending on values of strain and tilt values. In post-mining areas with medium and high risk, the monitoring should be performed due to safety of building and constructions, for example using InSAR technology and structure monitoring, for example for detecting tilt of buildings.

In Poland 3 categories of mine site of liquidated mines due to restrictions on use for mining purposes, according to Rules for documenting geological and engineering conditions for the purposes of mine closures, were issued by Ministry of Environment 2009. With regard to liquidated mines (underground, opencast, boreholes), the criteria for qualifying the areas of liquidated mines for development and reclamation are indicated. Categories of mining areas were introduced due to their suitability for development, as a result of deformations, land flooding, sinkholes resulting from the mine flooding. For various qualification criteria (e.g. ground movement-surface deformation, water conditions, soil conditions, mining influences, etc.), geological and engineering zoning was introduced, qualifying the areas of liquidated mines into areas suitable for development, areas conditionally suitable (after prior treatment) and areas unsuitable for development.

As there are no specific regulations on risk assessment of subsidence in post mining areas, specialists are supported by legal regulations related to the rules for documenting of geological conditions for the purpose of mine closure and Instruction No 12 GIG (Central Mining Institute, seria: Instrukcje Nr 12, 2000. Principles of assessing the possibility of conducting underground mining due to the protection of building structures (Zasady oceny możliwości prowadzenia podziemnej eksploatacji górniczej z uwagi na ochronę obiektów budowlanych) Katowice 2000). Other document supporting stakeholders was issued by Ministry of Environment and is entitled: Principles for documenting geological and engineering conditions for the purpose of mine closure (Zasady dokumentowania warunków geologiczno-inżynierskich dla celów likwidacji kopalń (2009, eds. Woźniak H., Nieć M., Warszawa, Ministry of Environment).

The scheme of actions at the stage of mine closure is as follows. Coal Mine company (specific coal mine), orders monitoring and analyse of different hazard, surface deformations between others, from specialised institutions or laboratories. By analysing the results of measurements, geological maps, technical and mining data of the studied area, specialists estimate the likelihood and potential future consequences of subsidence. All documents are obligatory forwarded to State Mining Authority and stored in the archives. There is no method for analysing the co-occurrence of subsidence and other hazards.

Hydrological disturbances

The most significant hydrological disturbance is the formation of floodplains in subsidence basins. Some of these are used as process water reservoirs. Others have ecological functions. Some are important recreational areas for the inhabitants of post-mining areas.

Other problems include fluctuations in the water level, the possibility of contamination of drinking water, groundwater etc. by mine drainage, leachate from waste dumps.

Mining companies are required to monitor the impact of spoil heaps on the environment, including the quality of groundwater and surface water. However, there is no regular network of piezometers in post-mining areas, and water level or chemical composition measurements are not conducted systematically.

Gas emission

In Poland, the measurement of methane and CO_2 on mining and post-mining areas is regulated by regulations concerning mining safety, environmental protection, and the management of mining waste. These requirements cover not only activities during mining operations but also the monitoring of gases after mining activities have ended, particularly in the context of spoil heaps and reclamation areas. The Waste Act, part of Mining Act of July 10, 2008, includes regulations on the management of mining waste, including spoil heaps, which may be a source of methane and carbon dioxide emissions. The obligation to monitor these gases is part of the broader oversight of post-mining waste management.

Ionizing radiation emissions

In Poland, there are no regulations regarding the control of radon emission levels in post-mining areas.

In general, according to Atomic law([Dz.U. z 2024 poz. 127]7), for radon concentrations in dwellings recommend value is 300 Bq/m³.

The Central Mining Institute (GIG-PIB), as part of its statutory work and research projects, identified radon-prone areas. It was found that areas with an elevated radon potential overlap with sites of shallow ores and coal exploitation. Additionally, in areas with Triassic carbonate formations, the migration of radon and its infiltration into buildings are easier compared to other geological structures. A map indicating areas with elevated radon potential, as locations that overlap with areas of both shallow exploitation and outcrops of Triassic formations has been developed – (Figure 3).

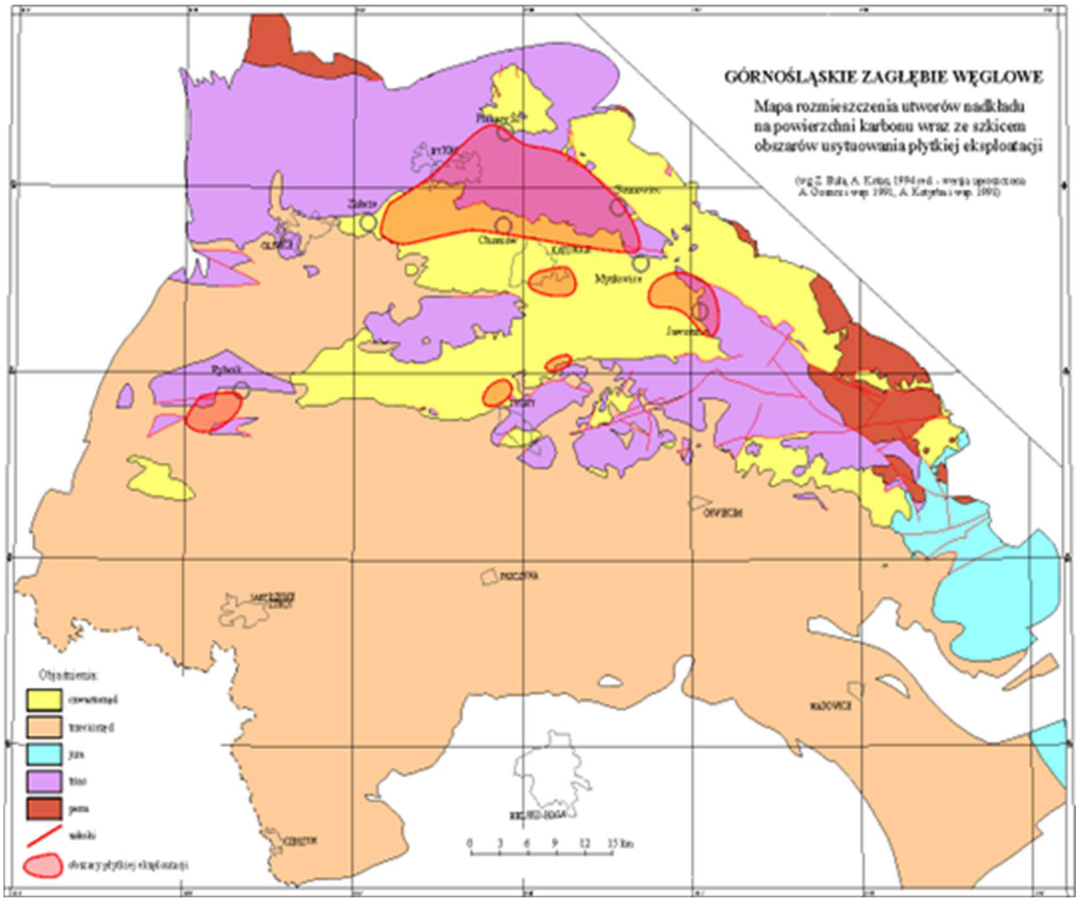

Figure 55 - The map of the overburden geological formations on the Carboniferous (based on Buła & Kotas, 1994) purple – Triassic formations, sites marked in pink – areas of shallow exploitation

Combustion and overheating of mine waste.

The issues related to the management and monitoring of spoil heaps are regulated by the Waste Act of December 14, 2014, Journal of Laws 2013, item 31.

The monitoring of spoil heaps during the process of mine closure is the responsibility of several entities, both public and private. The main entities responsible for this process are:

Mining company (or the owner of the mine) – This is the company that operates the mine or is carrying out the mine closure process. The mining company is responsible for monitoring the spoil heaps left after the mine is closed, including assessing their impact on the environment and conducting reclamation activities. According to the law, the company must ensure proper supervision of the heaps and other mining waste, including regular monitoring of water, air, and soil quality in the surrounding area. Other institutions involved in monitoring are: Voivodeship Inspectorates for Environmental Protection (WIOŚ), State Environmental Inspection (PIOS), in some cases Research and scientific institutions and Local governments

In summary, mining companies (mine owners) are primarily responsible for monitoring spoil heaps during mine closure, but oversight is also provided by state institutions.

After a mine is closed, the spoil heaps require special management to minimize their negative impact on the environment and human health. This process involves beetwen others monitoring of the condition of spoil heaps, including regular inspections of the temperature of the heaps. The risk of spontaneous fires is also analysed.

After the closure of the mine, some of the spoil heaps are being reclaimed. One of the measures that should be udertaken is fire prevention. Special attention is given to controlling the temperature and humidity of coal heaps to avoid fires.

Induced seismicity

In Upper Silesia (Poland) exists the method for the assessment of the impact of vibrations caused by seismic events induced by mining and post-mining tremors on buildings, linear objects of the underground infrastructure and the perceptibility of vibrations by humans. The scale distinguishes 7 grades for which, in correlation with vibration parameters, the impact of mining tremors on buildings and linear objects is described, as well as the intensity of the vibrations felt by people and the inconvenience of using buildings. The effects of vibration harmfulness expressed with the degree of harmfulness **S**, assigned to the instrumental measurement levels of the $\mathbf{I_{MSIIS}}$ seismic intensity, are different for different building structures and their technical conditions. The short version of the MSIIS-22 scale is intended to give a very generalized view of the scale. It was presented in: New mining instrumental seismicity scale – MSIIS-22 | PostMinQuake | RFCS project.

The actors involved in the post mining management of induced sieismicity hazard are: Mining Companies, State Mining Authority and owners of buildings and other real estates.

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.

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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

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