Post-Mining Multi-Hazards evaluation for land-planning

PoMHaz

WP2: Post-mining hazards and multi hazards identification and assessment methodology

D8 - Deliverable D2.3: Methodology of interaction between post-mining hazards

Authors: Marie Degas, and Marwan Al Heib, (Ineris)

Status: final
Report Date: 08.07.24

Confidentiality Level: public

This project has received funding from the Research Fund for Coal and Steel under Grant Agreement No 101057326.

Deliverable 2.3	
Due date of Deliverable	30.04.2024 (revised version after RFCS request)
Start – End Date of the Project	01.10.2022 – 30.09.2025
Duration	3 years
Deliverable Lead Partner	Ineris
Dissemination level	Public
Digital file name	Methodology of interaction between post-mining hazards
Keywords	Hazard assessment – hazard interaction – multi-hazard – post-mining

Content

List of Tables

List of figures

Acronyms

BRGM	Bureau de recherches géologiques et minières (France)
Cerema	Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement.
GEODERIS	French mining expert
NGO	non-governmental organisation
MLC	Mining life cycle
PPRM	Plan de Prévention des risques miniers (Mining Risk Prevention Plan)
RFCS	Research Fund for Coal and Steel

1 Executive Summary

The main objective of PoMHaz is to develop a management methodology to treat a global and multi-hazard related to abandoned coalmines instead of dealing with hazards separately. The overall objective is to improve the methodological knowledge for practical realization of multi-hazards analyses, at the scale of a mining basin, in correlation with the main kind of post-mining hazards. The work aims at testing and adapting the developed methodology by considering the different risks that affect the mining region.

The WP2, Post-mining hazards and multi hazards identification and assessment methodology, is dedicated to identifying post-mining single hazards and multi-hazards and assessing if they present a potential source of harm and if they have potential social-economic impacts after the mining closure. The main objectives of the work package are:

- To establish a knowledge base with a shared library of post-mining phenomena.
- To carry out a critical analysis of existing tools and methodologies for post-mining hazards identification, analysis and assessment.
- To develop a framework / methodology to identify and characterize possible hazard interactions.

The work done presented in these deliverable addresses:

- The definition and description of the hazard categories that can occur in the mining area: mining hazards, natural hazards, and technological hazard.
- The identification and evaluation of the hazard interactions: mining-mining hazards interaction, mining-natural hazards interaction, and mining-technological hazards interaction.
- The construction of the interaction diagrams.
- The evaluation of special and temporal scale interaction.
- Suggestion of a tool to map the hazard interaction.

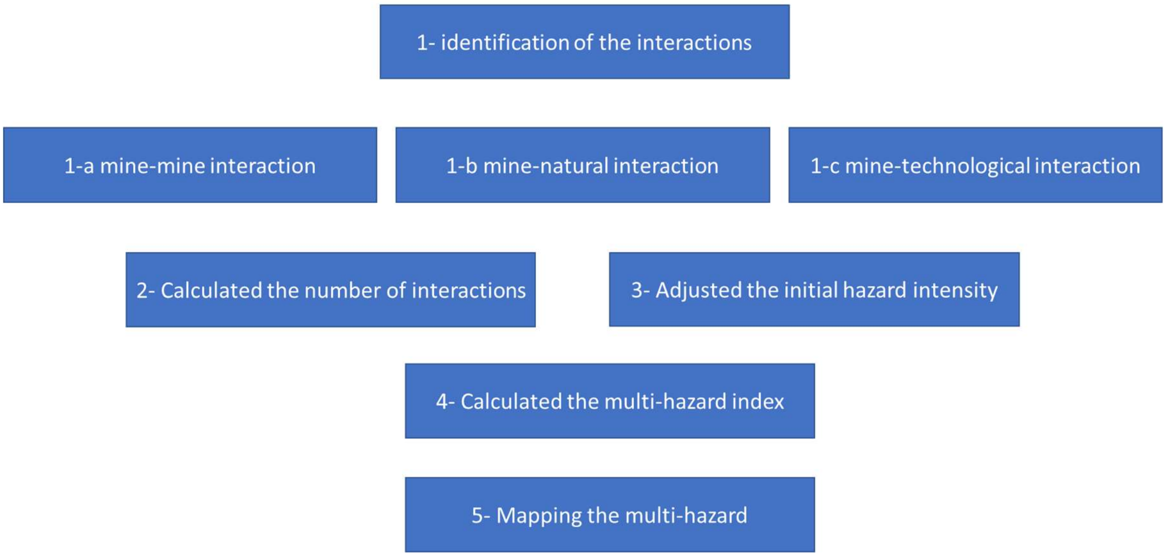
The results of the work done in this task showing that the assessment of the potential interactions of mining hazards with natural and technological hazards are very important for the management of the abandoned mining sites in Europe and all over the world. The identification of the potential interactions between hazards should be based on the partners knowledge, as experts of the mining, natural and technological hazards. Specific tools were presented in the deliverable e.g. the interaction matrix, the diagram of interactions.

The methodology of the multi-hazard for mining sites consists of five main steps:

- first, identification of the main mining, natural and technological hazards.
- second, the identification of the potential interaction based on the internal predisposition factors and external factors.
- third, the identification of the type and the level of the interaction. Three types of interactions were adopted: simple, double and cascading (domino). Three levels of interaction were also adopted: low (green), moderate (orange) and severe (red).
- fourth, the calculation of the multi-hazard intensity (MH); the calculation was developed taking into consideration the level of the initial hazard, the level of the interaction and the number of the existing hazards.
- And the mapping of the multi-hazard using existing technologies, for instance, GIS tool.

The Figure presents the main steps.

Multi-hazard assessment methodology



The application of the developed methodology needs a large effort for collecting the different information firstly to assess the level of the single hazards and then to build the matrix of interactions or the diagrams of interactions. Additionally, different scenarios can be (should) identified, described, allowing measuring the probability of occurrence for a specific site.

The document presents the development of multi-hazards interaction and assessment in former abandoned mines in order to:

- take stock of the consideration of the physical interactions between various hazardous phenomena and any regulatory incompatibilities or constructive provisions inherent in multi-risk.
- propose a methodology of multi-hazard assessment that considers the interactions between hazards around abandoned mines.

.

2 Background

2.1 Description of the WP2

WP2 is dedicated to identifying post-mining single hazards and multi-hazards and assessing if they present a potential source of harm and if they have potential social-economic impacts after the mining closure. The main objectives of the work package are:

- To establish a knowledge base with a shared library of post-mining phenomena.
- To carry out a critical analysis of existing tools and methodologies for post-mining hazards identification, analysis and assessment.
- To develop a framework / methodology to identify and characterize possible hazard interactions.

The work package has 3 tasks:

- Task 2.1. Knowledge base and library of post-mining hazards.
- Task 2.2. Critical analysis of existing tools and methodologies.
- Task 3.3. Development of a methodology for post-mining hazards interactions identification.

This deliverable concerns the Task 2.3.

2.2 Description of the T2.3

The previous study of the task T2.2 discussed the general methodology and tool used for assessing an individual hazard in general and post-mining hazard particularly. The analysis showed also that the analysis of multi-hazard is not used in mining and post mining sector. The deliverable 2.2 addressed more precisely:

- The post-mining hazard and the approaches and used tools across Europe to assess and integrate in a single and consistent framework several specific hazards / hazards interactions and their socio-economic implications.
- The gaps in terms of methods for evaluating specific hazards / hazards interactions, and their socio-economic consequences.
- The feedback and the critical analysis regarding the risk assessment for multi-hazards in the mining sector and, more precisely, in post-mining areas.

The work done presented in these deliverable addresses:

- The definition and description of the hazard categories that can occur in the mining area: mining hazards, natural hazards, and technological hazard.
- The identification and evaluation of the hazard interactions: mining-mining hazards interaction, mining-natural hazards interaction, and mining-technological hazards interaction
- The construction of the interaction diagrams.
- The evaluation of special and temporal scale interaction.
- Suggestion of a tool to map the hazard interaction.

In the second part of the report, an example of the application of this methodology on a mining site is provided.

3 Post-mining hazards

3.1 Definition of hazard

"Hazard" is a commonly used term in risk prevention. It means the probability that a phenomenon— in this case caused by mining activities — will occur on a site, during the course of a reference period, reaching a qualifiable or quantifiable intensity. Hazard characterization is traditionally based on the intersection of the predicted intensity of the phenomenon and its probability of occurrence (UNDRR, 2020, ISRM, 2008).

A phenomenon's intensity corresponds to the extent of the disturbances, aftereffects or nuisances that are likely to result from that potential phenomenon. This integrates not only the concept of the magnitude of potential events (e.g., crater size and depth, water level, nature, and content of gas emissions), but also their potential effects on people and goods.

In this context, the concept of probability of occurrence refers to the sensitivity of a site to be affected by a phenomenon. Whatever the type of mining-induced event, the complexity of mechanisms, and the heterogeneous nature of the natural surroundings, there is a lack of information and disturbances, aftereffects or nuisances are not repetitive. As a result, it is generally impossible to reason in terms of a probabilistic quantitative approach.

Therefore, we usually use, at least in France, a qualitative classification that characterizes a site's predisposition to be affected by a given phenomenon. This is the concept that will be used in this document.

A hazard is thus the result of the intersection between intensity and predisposition. The principle of hazard qualification consists of combining the criteria used to characterize first the intensity class of a potential phenomenon and then its predisposition class.

3.2 Categories of individual mining hazard

After the end of the exploitation, traditionally called "post-mining" phase, numerous disturbances can occur — sometimes as soon as mining work stops (Unger and Everingham, 2019), but sometimes much later (years). The PoMHaz presented the list of the post-mining hazards in the previous deliverable (D6-Deliverable D2.1: Data base of hazards related to closed and abandoned coalmines and lignite in Europe). Former coal mining sites can sometimes be affected by different related mining hazards such as: ground movement (subsidence, collapses), rising gas, irreversible disruptions in underground water circulation and water quality (pollution). The types of hazards depend on the mining method and eventually of the status (reuse, abandoned, etc.) of the mining site.
Figure 1 represents the main sources of mining hazards related to the post-mining phase:
-residual voids related to the goaf (collapsed zone above the extraction area) induced by the long-wall extraction method used for the recent deep coalmines in Europe.
- room and pillar method used for shallow coalmines, the pillars can collapse and induce ground movement.

- lake resulting from the flooding of open pit mine: the lakes can constitute different mechanical, hydrological and environmental post-mining hazards.

- wastes: the wastes are related to ground, open pit mines, energy plants, treatment of coal, etc. They can constitute geomechanical and hydrological hazards and can be source of pollution, etc.

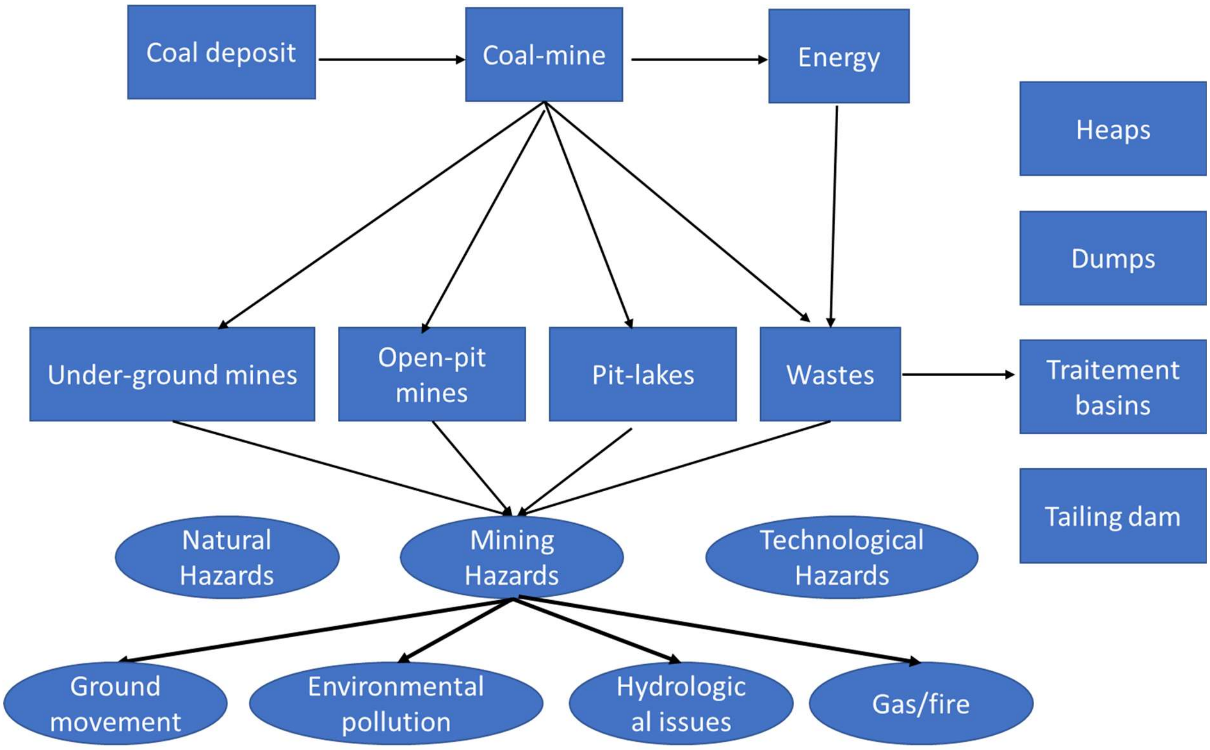


Figure 1. Main sources of hazards related to post-mining phase in the coal mine sector (coalmine refers to extraction, coal refers to the coal treatment, and energy refers to the ashes[1] from the plants).

The post-mining hazards can interact with different natural hazards (flooding, earthquake, landslide, etc.) and technological hazards (Lenhardt, 2009, Aydan et Tano, 2012, Azharia and Ozbay, 2017, Zeng et al., 2018, Spandis et al., 2019, Morgan and Dobson, 2020, John, 2021, Valverde et al. 2021, OECD, 2022). The interaction between the different categories of hazards: mining, natural and technological hazards will be presented in the following section of the document.

[1] Coal ash, also referred to as Coal Combustion Residuals (CCR), is the material produced primarily from the burning of coal in coal-fired.

4 Multi-hazards assessment in mining area

4.1 Context and Objectives

In mining context, the risk and hazard assessment studies have focused on the detailed examination of a single hazard phenomenon. However, the abandoned mining areas is generally not affected by one mining or natural hazard, but two or more can act at the same time or consecutively. For instance: natural hazard (earthquake) can trigger a mining hazard (landslide of a dump). Or a mining hazard (subsidence) can increase the intensity of natural flooding hazard. Additionally, the mining hazards have a large impact on the social and economic activities and the urban development of mining regions (Aldridge et al., 2016, Camm et al., 2000).

Based on the context and the European Green Deal objectives (EGDO), the benefits of multi-hazard/multi-risk analysis around abandoned mines can be summarized as follows:

- better assessment of the intensities and predisposition of hazards around abandoned mines, through scenarios associated with their interactions.
- better consideration of the vulnerability of the challenges of a territory exposed to several hazards.
- more comprehensive consideration of interactions between mining, natural and technological hazards.
- global and integrated view of the risk which leads to a better preservation of the general interests identified around abandoned mines.
- improvement in the resilience capacity and sustainability of the territories.
- improvement of the communication plan and the decision-making.
- selection of the best options in terms of mitigation solution and risk management.

A joint analysis and quantification of all the anthropogenic and natural risks which can affect a territory (multi-risk approach) is a basic factor for the development of a sustainable environment and land use planning as well as for a competent emergency management before and during catastrophic events (Durham, 2003).

Marzocch et al. (2009) studied the principles of multi-risk assessment and interaction amongst natural and man-induced risks. They argued that mitigation actions have to be focused not necessarily on reducing the highest rank risk. They also argued that mitigation actions have to be decided considering the multi-risk assessment with a sound cost/benefit analysis.

Thus, the assessment of one mining hazard can be unmanageable when multiple hazard types have to be considered. However, a multi-hazard approach, in a post-mining context, is not obvious: the available data for the different single hazards may refer to different spatial scales. The comparisons, the rankings and the aggregations can be difficult; different specialized organisations and experts need to collaborate to assess the interaction between hazards.

The main objective of PoMHaz, and more precisely the WP2, is to develop a management methodology to treat a global and multi-hazard related to abandoned coalmines instead of dealing with hazards separately. The overall objective is to improve the methodological knowledge for practical realization of multi-hazards analyses, at the scale of a mining basin, in correlation with the main kind of post-mining hazards. The work aims at testing and adapting the developed methodology by considering the different risks that affect the mining region.

4.2 Hazards categories in mining area

The first step is dedicated to the description of the three major families of hazards: mining hazards, natural hazards and technological hazards.

In fact, the main hazards which may occur in former mining operations are grouped into 3 large families for which the assessment methods are different: mining hazards (M), natural hazards (N) and technological hazards (T). The different hazards can interact with each other leading to a higher level of danger. In the abandoned mining areas, mining hazards can interact with other mining hazards and with both natural hazards and technological hazards. The possible interaction between the hazards is made according to:

i) their nature (triggering or aggravating);
ii) their category (physical or regulatory);
iii) and their typology (dependent or independent).

In an abandoned mining area, several mining hazards can be identified and may interact (Lazar et al., 2015, John, 2021). The expert feedback needs to be used to establish the interaction between mining-mining hazards and mining-natural hazards, mining-technological hazards. Furthermore, in mining sectors if the interaction between hazards is considered as relevant, two situations can be observed:

- mining hazard triggers another mining hazard, and/or another natural hazard or technological hazard.
- mining hazard increases a factor instantaneously or in a delayed manner a natural hazard or a technological hazard.

Figure 2. An overview of mining pollution and associated hazards (Rebello et al., 2021)

The Table 1 summarises the different hazards which may occur in the mining site. Natural and technological hazards can exist without the existing of the mining hazards.

Table 1. Different, major mining, natural and technological hazards

Mining hazards (18)	Code	Natural hazards (17)	Code	Technological hazards (17)	Code
Subsidence	SUB	Subsidence	SUB	Gas explosions	EXP
		Localised collapse (sinkhole)	SIN	Slick fire (liquid)	FEN
Crevasse	CRE	Dissolution (e.g., gypsum, chalk or salt)	DIS	Flare fire (gas or liquid)	FET
Localised collapse (sinking)	SIN	Clay shrinkage or settlement	SET	Solid fire (combustible solids)	FES
Massive mine collapse	MMC	Deep-seated landslide	DLS	Boil over (heavy hydrocarbons)	BLO
Settlement linked to mining works	SET	Shallow landslide	SLS	BLEVE (flammable liquefied gases)	BLV
Deep-seated landslide	DLS	Erosion	ERO	Liquid product release with vaporisation of the liquid jet	RPL
Shallow landslide	SLS	Mudflow	MUF	Gaseous product release	RPG
Erosion	ERO	Rock slide	RLS	Release of a liquefied gas	RGL
Mudflow	MUF	Rock fall	RFA	Fire with the decomposition of toxic products	IPT
Rock slide	RLS	Avalanche	AVA	Release of radioactive substances or nuclear radiation	RSR
Rock fall	RFA	Earthquake	NSI	Discharge of water bodies	RME
Heating of veins or slag heaps	COM	Forest fire (wildfire)	FFI	Land movement due to human activities	MVT
Mine gas	GAZ	Settlement, consolidation	SET	Tank burst (Pneumatic energy release)	EBC
Modification of the groundwater discharge regime	MWR	Lowland flooding, as opposed to torrential flooding	FLO	VCE (Combustion of gases, vapours)	VCE
Modification of the regime of a river	MOR	Flooding by runoff and mudslides		BLEVE (explosive vaporisation of boiling liquid)	BLV
Flooding of topographic low points	TFL	Flooding by rising groundwater		An explosion of solids (ammonium nitrate, pyrotechnics	ENA
Flash flooding – submergence	FFS				
Induced seismicity in former mining operations	INS				

4.2.1 Mining hazards (M)

The Table 1 provides a list of hazardous phenomena, scientific disciplines covered and their consequences. Additional mining hazards can occur for special activities. The consequences of the mining hazards can involve the people, the structures, the infrastructures, the agriculture lands, the environment, the water and the air. Additionally, the interaction with natural and technological hazards can, under specific conditions, increase the impact of the post-mining hazard. The main example cited by the TEXMIN project (www.texmin.eu) is the following. On 18th of July 2019, on the southern slope of the Nachterstedt open-cast mine, a large-scale slope movement took place in which three residential buildings in a housing estate were destroyed. A total of 4.5 million cubic meters of soil started to move and caused a large-scale landslide event.
The following main residual hazards or environmental impacts are considered (PoMHaz):

- **ground movements hazards**: the mining activities create voids to extract the coal, some of them are treated and filled, however residual voids still exist. The residual underground voids, rock faces or deposits of mining residues can cause **ground movements** (slope instability, subsidence, etc.) which may endanger the safety of people or cause damages to buildings and infrastructures (cracks, collapses, etc.).
- **hydrological and hydrogeological hazards:** the shutdown of a mine is accompanied by the stopping of the pumping of underground water from the work site; and in the general mining area, there may be a decrease in water consumption by the community and industries in the area. Consequently, the mine closure is accompanied by a rise in the water table level, which has gradually returned to its natural level, partially or completely refilling the reservoirs and voids created by mining and rejoining the hydrographic network on the surface or topographical low points that may have been created by the mining. These **hydrological and hydrogeological disturbances** may be detrimental to land use or subsoil use.
- **gas emission hazards**: the extraction of underground ore has contributed to create a reservoir that may be filled up with gas issuing from the exploited rock or from farther away. This gas is a mixture of multiple components with varying contents. Under the effects of various mechanisms, mine gas may be directed towards the surface via natural drains (faults, fractures, cracks, etc.) or artificial drains (shafts, galleries, etc.). Mining may also have generated new drains (cracks, crevices) that link underground gas-emitting formations with the surface. These **gas emissions** are potentially dangerous. Furthermore, the natural gases present in the surrounding rock mass are sometimes able to move more freely because of destruction caused by mining.
- **pollution of the soil, water, and air**: the extraction or storage of large quantities of solid waste generates physical and chemical instabilities that can cause lasting disturbances in the natural surroundings. One of the causes of post-mining pollution and nuisances is the interaction between mining operations and hydraulic flows, which can lead to contamination of the soil, surface water and groundwater. Surface conditions (air, precipitation) may influence **the discharge into the environment of substances that are potentially damaging or dangerous** to people and/or ecosystems. It should be noted that the environmental and health impact of pollution associated with mining activities is the subject of a specific risk assessment and management approach that is different from that carried out via the study of hazards. In France, the approach applied to former mining sites is inspired by the methodology for managing polluted sites and soils. This is why the hazard assessment guide does not deal with soil and groundwater pollution.

- **Self-heating**: one of the major hazards that may affect the coal dumps/spoils is the fire and combustion of the dump material. Residues from coal and lignite mines containing horizons sufficiently rich in solid carbonaceous elements (coal, lignite) are likely to be affected by in situ combustions.

Ineris (2023) summarized the importance of the main hazards related to post-mining phase, based on data collected from the international literature (Figure 3). It thus appears the main post-mining hazards concern the surface water (35%): contamination of watercourses and water bodies, modification of the route or the slope watercourses, appearance of lakes or wetlands. The second hazard concerns the ground surface: ground movement, alteration of ecosystems and landscapes.

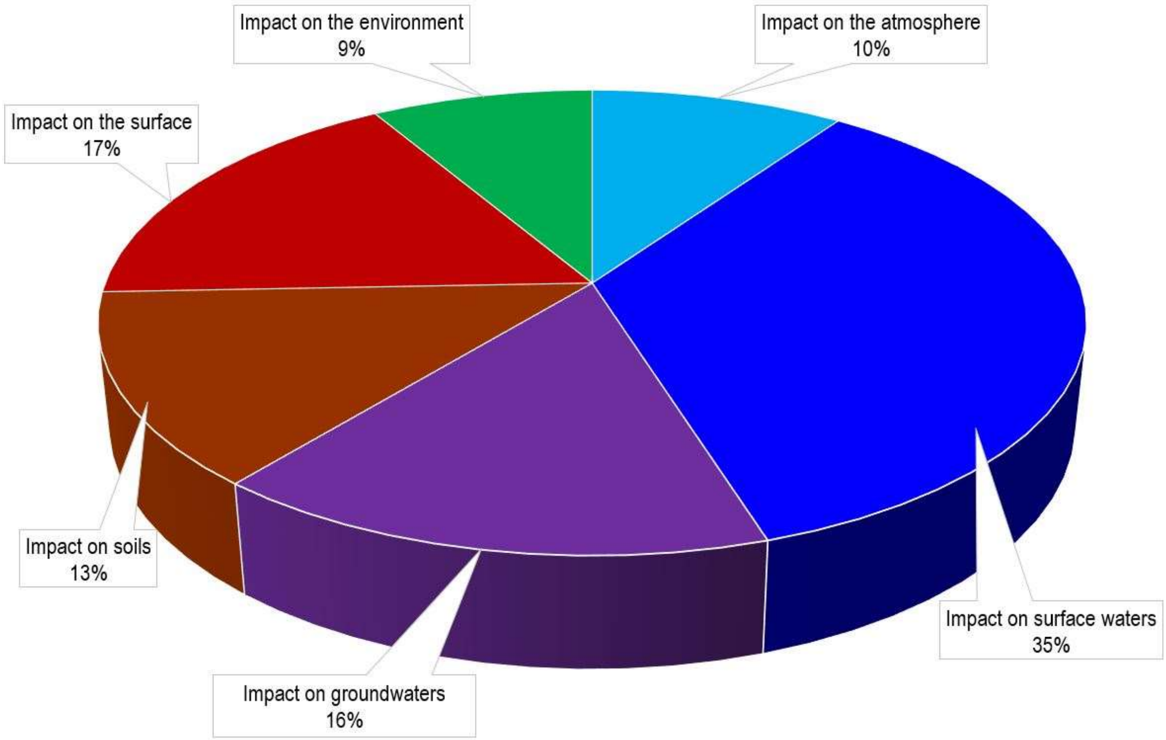


Figure 3. Mains hazards related to the post-mine assessments (Ineris, 2023)

Based on the work done of the PoMHaz, Task 1.1, different potential mining hazards can occurr in abandoned mining areas (El Shayeb et al., 2004, Abdul-Wahed et al., 2006, Al Heib et al., 2005, ISRM, 2008, Bétournay, 2009, Mutke and Bukowski, 2011, Lagny et al., 2012, Spanidis et al., 2019, Morgan and Dobson, 2020). The hazards likely to develop in the case of a mining operation, or by ancillary facilities, abandoned are generally gathered into 6 groups (M1-M6):

M1) ground movements.

M2) combustion and fire in mine deposits and dumps.

M3) hydrological and hydrogeological disturbances of mining origin.

M4) gas emissions in connection with mining.

M5) endogenous radioactivity of the environment.

and M6) environmental pollution from mining on water, soil and air.

Ground movements (M1): different ground movements can occur in former mining lands (Figure 4 and Figure 5). The main predispositions factors of mining hazards are presented in Figure 6.

- Localized collapse (sinkhole M1-1): it is a brutal movement due to the presence of exploited areas at shallow depth (<50m). The localized collapse manifests itself in the sudden sinking of several meters in a relatively limited area (dimensions ranking from one meter to a few tens of meters). This type of phenomenon can also be linked to the presence of an old mining shafts. The dimensions of a localized collapse depend on the size of the underground cavity and the nature of the overburden / topsoil that separates the void from the surface. The sinkhole may cause damages to people and structures.

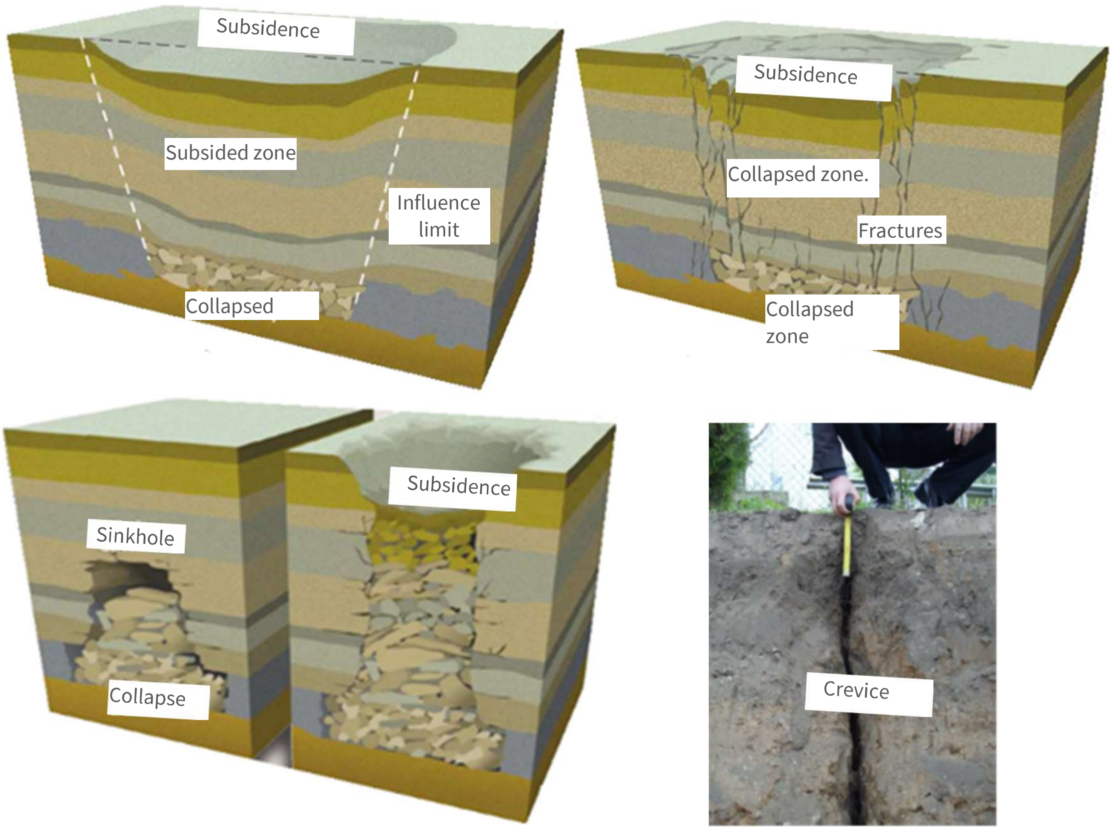


Figure 4. Ground movement hazard (subsidence, sinkhole, crevices, large collapse) related to underground mines and cavities, sinkhole" (source: Graphics, MEDD)

- Subsidence (M1-2): subsidence is a movement of land linked to the presence of large, exploited areas often at greater depths (from a few tens of meters to several hundred meters). It manifests itself in the gradual consolidation and compaction of the overburden and the formation of a flexible and continuous subsidence basin. The subsidence caused by the collapse of old mining operations, especially mines with abandoned rooms operated according to the pillar method.
- Generalized collapses (M1-3): they are also caused by the collapse of a room and pillar mine. However, they occur in very specific geological conditions, manifesting themselves by an often dynamic and near-instantaneous collapse of all or part of an exploitation (between the bottom and the surface), thus affecting the stability of surface land over areas that can extend up to several hectares. A seismic tremor may be felt. The part of the collapse affecting the central area may reach several meters in height, or even several tens of meters in the case of collapses of salt dissolution

cavities. These phenomena can cause physical dangers and lead to the "irreversible" destruction of property and surface land.

- Crevices (M1-4): in specific cases, mining may lead to crevices in the overburden when subsidence bowls are formed. Some crevices appear on the surface during exploitation, but some do not open or appear until several years later. Crevices take the form of cracks in the soil several decimetres wide and several meters long. The "visible" depth of these crevices is several meters, but the actual depth is unknown.
- Settlement (M1-5): settlement is like subsidence hazard but with lesser magnitude. This phenomenon is linked to the decompaction of materials either at shallow depth (backfilled or collapsed galleries for example), or on waste rock storage (heaps, slurry ponds). Settlements can be associated to old mining works or to the presence of heaps movements.
- Landslides (M1-6): they are generally encountered on deposit structures (slag heaps, slurry ponds), or surface mines (Figure 5). The extraction or storage of large quantities of solid waste generates physical and chemical instabilities that can cause lasting disturbances in the natural surroundings and landslides. The slope instability can be slow. It may also involve very rapid movements leading to the displacement of materials. Superficial slide corresponds to the entrainment of a little material (gullying for example), or deep-seated landslide when the volumes are greater. The movements at the face of open-cast operations that may occur during or a long time after the work has stopped: gullying linked to runoff, landslides, boulder falls, mass collapse.
-

Figure 5. Ground movement hazard related to open-pit mines and dumps, lakes, etc.

Depth of cavity (ies) Width / diameter/height Geology (layer/overburden) One cavity/multi-cavities	Mining method Mining surface / dimensions Mining depth Geology/faults	Slope angle Height Soil/rock quality Geology/faults
Sinkhole-M1-1	Subsidence-M1-2 Generalized collapse-M1-3 Crevasse-M1-4 Setlement-M1-5	Landslide-M1-6

Figure 6. Main predisposition factors of mining ground movement (M1)

Water hazards and hydrological and hydrogeological disturbances/Flooding (M2): The Figure 7 represents the main predisposition factors of the mining water hazards. These disturbances of mining origin concern the modification of emergences, the flooding of topographic low points or points of the basin, the modification of the regime of a watercourse and brutal floods such as the failure of structures at the bottom but also on the surface.

Flooding mine
Nature of terrain
(permeability)(permeability)
Water pumping
Near water tables
Topography / Geomorphology
Hydraulic infrastructures

Figure 7. Main predisposition factors of mining water hazard (M2)

Self-heating (M3): this hazard is mainly linked to the heating of land on mining deposits, the hazard concerns mainly coal and lignite mines (Figure 8). Heating is a phenomenon linked to the combustion of coal residues contained in certain waste rock deposits. Thus, very high temperatures (several hundred degrees) can then be reached. Other hazards can be triggered in relation to combustion hazards, heating of the coal veins can, for example, cause land collapses and subsidence on the surface, overheating of slag heaps. Some mining deposits contain combustible materials and other oxidizable substances such as iron sulfides (pyrite). Some deposits may actually combust (with contact from an external heat source or after modifications of the deposit initiating self-heating phenomena). Combustion in a waste heap can spread slowly from the surface to the very bottom. In this case, the combustion can continue for several decades. The principal risks associated with this phenomenon are burns, falls into cavities created by combustion, and fire, linked to toxic or flammable gases.

Coal dump
Existing residual coal

Figure 8. Example of self-heating hazard – (source: GEODERIS), main predisposition factors (M3)

Gas hazards (M4). Sometimes elevated emission of radon, radioactive noble gas, entering dwellings is observed. When mines are shut down, non-inundated underground voids can form a more or less confined reservoir in which gases (which are diluted or evacuated by ventilation during exploitation) may accumulate at high concentrations and, when they rise to the surface through underground galleries or through natural faults or fractures in the rock, become potentially dangerous, causing intoxication, asphyxia, inflammation or explosion.

Mine gas is generally a mixture of gases of varying origins and contents. Some gases are present in the deposit before mining starts (methane (CH_4), carbon dioxide (CO_2), etc.); others are produced by a chemical transformation of the deposit or certain elements of the mine, during or after mining (carbon monoxide (CO), hydrogen sulfide (H_2S)).[2] Mining can also create connections between the surface and geological layers that are likely to emit gas.

Discontinuities (orientations, filling materials, etc.)
Nature of the terrain (rocks)
Shafts/galleries/boreholes,
Drainage
Geology / faults

Figure 9. Gas mine hazard and main predisposition factors of gas hazard (M4)

Radioactivity (M5): uranium mines are the main sources; radon also emits ionizing radiation in uranium deposits, in granite zones and in iron basins. Radon is a naturally occurring, heavy and hazardous inhalation radioactive gas that results from the natural breakdown of uranium and thorium.

Pollution of water, air and soil (M6): water infiltrates the flooded mining lands. They are then loaded with different chemicals. They can potentially pollute groundwater and water sources. This can also impact the food chain and there may also be dust that can be deposited in homes. One of the causes of post-mining pollution and nuisances is the interaction between mining operations and hydraulic flows, which can lead to contamination of the soil, surface water and groundwater. Surface conditions (air, precipitation) may influence the discharge into the environment of substances that are potentially damaging or dangerous to people and/or ecosystems.

A review of the relevant literature identified the following climate change-related threats to mining activities: landslides, where different kinds of mass movements are included i.e., mudflows or debris flows, landslides, landslips, and rock falls, flooding events (flash floods and river floods), cyclones, extreme winds, and storm surges where coastal flooding is included, wildfires, heat waves, cold spells, sea level rise (SLR), permafrost thaw, droughts and water scarcity (Mavrommatis et al., 2019). There are three types of natural hazards linked to climatic factors: floods, drought, and atmospheric hazards.

4.2.2 Natural hazards (N)

The natural hazards are events that are harmful to man and caused by forces extraneous to him. Dangerous natural hazards causing damage are mapped at all territorial scales. The Table 1 presents the main list of the natural hazards. At the scale of the territory, as around abandoned mines, natural hazards depend on the anthropogenic and the climate change factors. Natural hazards are naturally occurring phenomena caused either by rapid or slow onset events which can be geophysical (earthquakes, landslides, tsunamis and volcanic activity), hydrological (avalanches and floods), climatological (extreme temperatures, drought and wildfires), meteorological (cyclones, lightning and storms/wave surges) or biological (disease epidemics and insect/animal plagues). In the frame of the project, we identified the major well known natural hazards.
The natural hazards are gathered into 6 main groups (N1-N6).

[2]The most well-known gas is probably "firedamp," which is primarily composed of methane released in coal mines and may cause an explosion in ambient air (traditionally called a "firedamp explosion").

Ground movements (N1) refer to any more or less brutal movement of the ground or the subsoil, or of rocks destabilized under the effect of natural stresses (snowmelt, abnormal rainfall, seismic shocks, erosion at the foot of the slope, etc.). Ground movements can be grouped around five groups:

- Collapse of underground shallow natural cavities (N1-1): for France, the man-made cavities such as underground quarry, caves are considered natural hazards and not anthropogenic hazard.
- Landslide (N1-2), particularly large landslide mass (several million m^3), rock falls (volume less than 1 dm^3) and boulders (volume greater than 1 dm^3).
- Landslide (N1-3), corresponding to the movement of loose or rocky terrain along a fracture surface mainly due to high water saturation of the soil; they also include mudslides.
- Progress of a coastal dune front inland (N1-4).
- Differential settlements (N1-5) or shrinkage and swelling of clays.

The second group corresponds to flooding hazard (N2): this hazard is one of the main natural hazards over the world. The national territory is subject to several types of flooding (lowland flooding, torrential flooding, marine submersion, rising groundwater, etc.). As a result of a changing climate, scientists forecast more frequent extreme and erratic weather events. Flooding has always been the number one threat to mines. The impact of these flooding events can be expected to intensify.

Seismicity (N3) hazard refers to seismic hazard: this hazard associated with potential earthquakes in an area.

Wildfire hazard (N4) refers to a large, destructive fire that spreads quickly over woodland or bush.

Periods of drought (N5) can result from a lack of rain, irregular rainfall, or too intensive or inadequate use of available water. The phenomena of drought can be linked to shrinkage / swelling of clay soils. The drought hazard can also be linked to the hydrological and hydrogeological disturbance hazard.

Atmospheric hazards (N6) include a variety of wind-related hazards: cyclones and hurricanes, storms and squalls, waterspouts, lightning, hail, snow, freezing rain, forest fires.

The natural hazards depend also on the climate change (climate change refers to long-term shifts in temperatures and weather patterns). The TEXMIN RFCS project analysed more specifically the impact of the climate change on European abandoned and active mines.

4.2.3 Technological hazards (T)

The Table 1 presents the main list of the technological hazards. The technological hazard (European commission, 2010) is a hazard originating from technological or industrial conditions, including accidents, dangerous procedures, infrastructure failures or specific human activities, that may cause loss of life, injury, illness or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.
The technological hazard corresponds to all the effects (thermal, overpressure and toxic) that can occur at a given point in the territory around industrial sites including mining site. We regrouped the technological hazards in four main hazards.

Thermal effect hazards (T1): thermal effects are linked to the more or less rapid combustion of a flammable or combustible substance. They cause internal or external, partial or total burns to exposed persons.

Hazards with toxic effects (T2): toxic effects result from a leak in an installation or the release of a toxic substance resulting from chemical decomposition during a fire or a chemical reaction. Phenomena leading to a toxic effect are linked to the accidental release of a toxic chemical following, for example, a burst pipe or the destruction of storage tanks. The substance may then be released in liquid form and has to evaporate to disperse into the atmosphere or may be released directly in gaseous or two-phase form.

Hazards with overpressure effects (T3): overpressure effects result from a pressure wave (explosion or detonation depending on the speed of propagation of the pressure wave), caused by an explosion. This can be the result of an explosive, a violent chemical reaction, violent combustion (combustion of a gas or a cloud of dust), sudden decompression of a pressurized gas (bursting of a bottle of compressed air for example). The effects of overpressure can be direct and cause damage to the eardrums and lungs, the projection of people on the ground or against an obstacle. They can also be indirect, such as the collapse of structures or the impact of projectiles on people. They are the consequence of an explosion and are manifested by the very high-speed propagation in the atmosphere of a pressure wave. The pressure is estimated by considering the ratio of force per unit area likely to induce bending or shearing forces in the structures and, possibly, compression-type stresses on the human body. A pressure wave can also propel projectiles. The overpressure effect is linked to an explosion, the origin of which can be of a different nature with, among other things:

• the release of pneumatic energy following a burst of a pressurized tank;

• the decomposition of explosive substances or unstable products;

• the combustion of gases, vapours, powders, etc.

Hazards related to structures (T4): hazards related to structures are part of a new category of "non-industrial" overpressure hazards. It is created for the distinction of other hazards in agreement with the Ineris experts in technological hazards. These events, which include breaks in civil engineering structures such as dams, dykes, bridges, and viaducts (even if managed by road risk), but also geothermal drilling, bridge, and tunnel communication structures. The rupture or degradation of these structures may be in direct or indirect interaction with technological, natural or mining hazards.

4.3 Mining hazards interactions

In order to analyse and assess the potential interactions between, mining, natural and technological hazards, the experts of Ineris got involved through several meetings. In a second stage, Ineris worked with the project's partners (CERTH, GIG, THGA, PPC and SRK) to discuss the results obtained by the Ineris experts with two tools presented in the previous deliverable (T2.2):

- Matrix of interactions.
- Diagram of Interaction.

4.3.1 Mining-mining hazard interaction

The interaction matrix is composed of 6*6 mining hazards. In this case, theoretically, 36 potential interactions, corresponding to the boxes of the interaction matrix, should be studied (Figure 19). The rows of the matrix correspond to the primary hazards, which means that the hazards will be the first hazard that can occur on the mining site and can trigger a secondary hazard among the columns. This means that each main hazard can trigger one or more hazards immediately or later. Three levels of interactions are also considered: low interaction, green; medium interaction, orange and high interaction, red.

Based on the expert feedback, only 12 interactions were judged as possible due to the predisposing factors: 6 high-level interactions, 3 medium (moderate) level and 2 low interaction level.

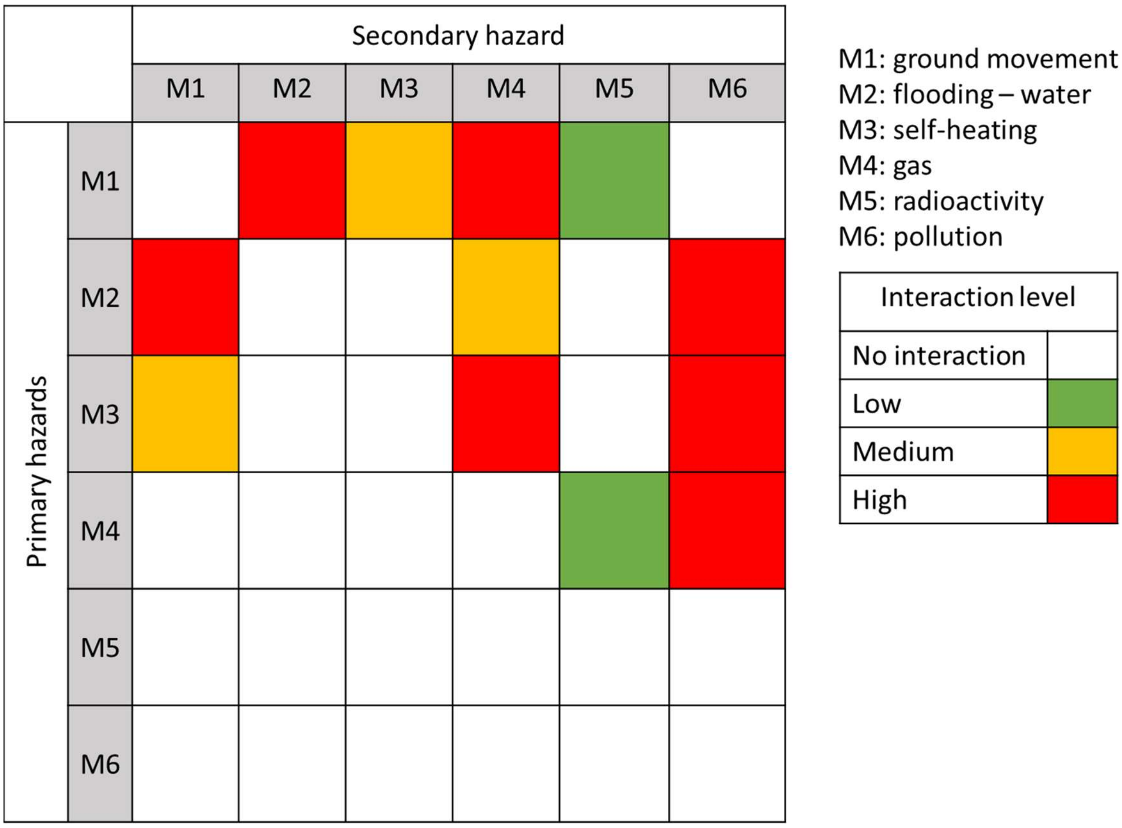


Figure 10. Interaction matrix between the main 6 mining hazards (M1 to M6).

The following interactions are identified for a mining hazard as a trigger to another mining hazard:

- ground-movement: the mining ground movement can interact with four mining hazards:
    - ground movement-flooding (M1-M2): the ground movement occurrence (e.g. galleries collapse, shaft collapse, subsidence) can damage the mining water system and tailing dam. Consequently, the ground movement hazard can trigger the flooding of abandoned mines. This interaction can be a domino interaction or an aggravation of the flooding hazard factor. The level of interaction can be considered a high-level interaction (RED).
    - ground movement-self-heating (M1-M3): the ground movement occurrence (landslide, crevice) can increase the air penetration through the coal dumps, including a high quantity of coal, and self-heating predisposition. Consequently, the ground movement hazard can trigger the self-heating of abandoned coal mine. This interaction corresponds to an aggravation of the self-heating hazard. The level of interaction can be considered a moderate-level interaction (ORANGE).
    - ground movement-gas (M1-M4): the ground movement occurrence (general collapse, sinkhole, crevice) can increase the permeability of the terrain and gas hazard predisposition, mainly the gas flow. Consequently, the ground movement hazard can trigger the gas hazard of abandoned coal mine. This interaction corresponds to an aggravation of the gas hazard. The level of interaction can be considered a high-level interaction (RED).
    - ground movement-radioactivity (M1-M5): the ground movement occurrence (general collapse, sinkhole, crevasse, landslide) can increase the permeability of the terrain and

radioactivity hazard predisposition. Consequently, the ground movement hazard can trigger the radioactivity pollution. This interaction corresponds to a slight aggravation of the radioactivity hazard. The level of interaction can be considered a low-level interaction (GREEN).

Interactions Summary: 2 high (RED), 1 medium (ORANGE) and 1 low (GREEN)

Concerning the interaction between two ground hazards (cavity and slop stability), Ineris (2017) has developed a methodology for assessing the interaction between the underground cavity and landslide of a cliff (mainly rocky one, Figure 11). The first step is the assessment of single hazards (collapse of the cavity and the collapse of the cliff). This evaluation is based on the geomechanical and geotechnical factors. Then the assessment of the interaction which depends mainly on the distance between the cliff and the underground cavity (D), where the hazard related to the cavity is defined by the distance (M1), and the hazard related to the slope is defined by the distance M2. The two hazards interact if M1+M2 ≤ D, otherwise, one considers the interaction is negligible (Figure 11).

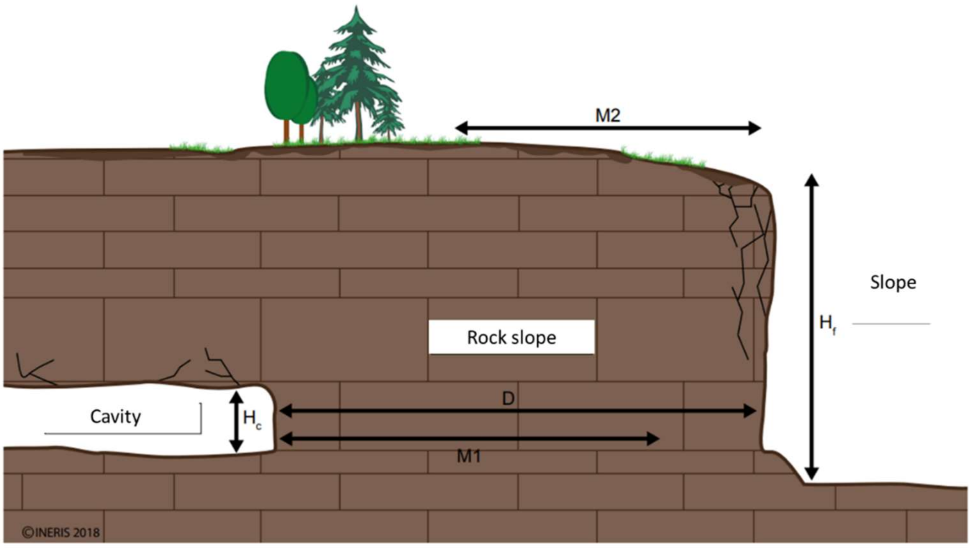


Figure 11. Assessment of the interaction between two hazards: cavity collapse and landslide of a rocky slope. The method is based on the calculation of the distance between slope and cavity (D)

- flooding – water system modification: this mining hazard can interact with three mining hazards:
  - flooding-ground movement (M2-M1): the flooding hazard occurrence (e.g. water system of the mine, tailing dam) can modify the rock and discontinuities behaviour of the rock mass and the faults, mainly by decreasing the strength capacity or by reducing the cohesion. Consequently, the flooding hazard can trigger the ground movement hazard of abandoned mine. This interaction can be a domino interaction or an aggravation of the factor of the ground movement hazard such as the compaction of the backfilling material or the goaf for the long-wall coal mines. The level of the interaction can be considered a high-level interaction. (RED)
  - flooding-gas (M2-M4): the flooding hazard occurrence (e.g. water system of the mine, tailing dam) can modify the atmosphere in the abandoned underground mines and increasing the pressure of the gas. Consequently, the flooding hazard can trigger the gas hazard. This interaction can be an aggravation of the factor of the gas hazard, the predisposition and the intensity of the gas hazard. The level of interaction can be considered a moderate-level interaction. (ORANGE)

- flooding-ground movement (M2-M6): the flooding hazard occurrence (e.g. water system of the mine, tailing dam) can modify the water level, water inflow of water tables. Consequently, the flooding hazard can trigger water pollution of abandoned mine. This interaction can be a domino interaction or an aggravation of the ground movement hazard. The level of interaction can be considered a high-level interaction. (RED)

Interactions Summary: 2 high (RED), and 1 moderate (ORANGE)

- self-heating: this mining hazard can interact with three mining hazards:
  - self-heating-ground-movement (M3-M1): the self-heating of dump, containing enough coal, can reduce the soil strength (friction angle, cohesion, etc.), that can modify the hydromechanical characterisation of the soil (permeability) and can modify the slope morphology (increase or decrease the angle of the slope). Additionally, they can modify the vegetation (such as trees). Thus, the self-heating hazard can trigger ground movement, mainly slope instability. This interaction can be a domino interaction or an aggravation of the factor of the ground movement hazard. The level of interaction can be considered as moderate-level interaction. (ORANGE)
  - self-heating-ground-movement (M3-M4-M6): the self-heating of dump, containing enough coal, can produce chemical reaction, toxic gas production, heavy metal and dioxins particles emission that can trigger a contamination of environmental compartments (air, soil, surface water, sediments, groundwater, biodiversity and foodchain) (Ineris, 2023). This interaction can be a domino interaction or an aggravation of the factor of the ground movement. The level of interaction can be considered as high-level interaction. (RED)

- Interactions summary: 2 high (RED), 1 moderate (ORANGE)

Ineris (2023) established the interaction between the self-heating (combustion) mining hazard and the different natural hazards (e.g. hot-zone, instabilities), man-made technological hazards, such as man-made fire or explosion of industrial installations (Figure 12). For instance, a natural fire (forest) can be the cause and the trigger event for the occurrence of the fire (combustion) of the coal dump that can trigger a landslide or/and a sinkhole. The case study reported in 2023 corresponds to the drought conditions due to the increasing of the temperature and lignite self-heating of an abandoned coal-mine in southern France.

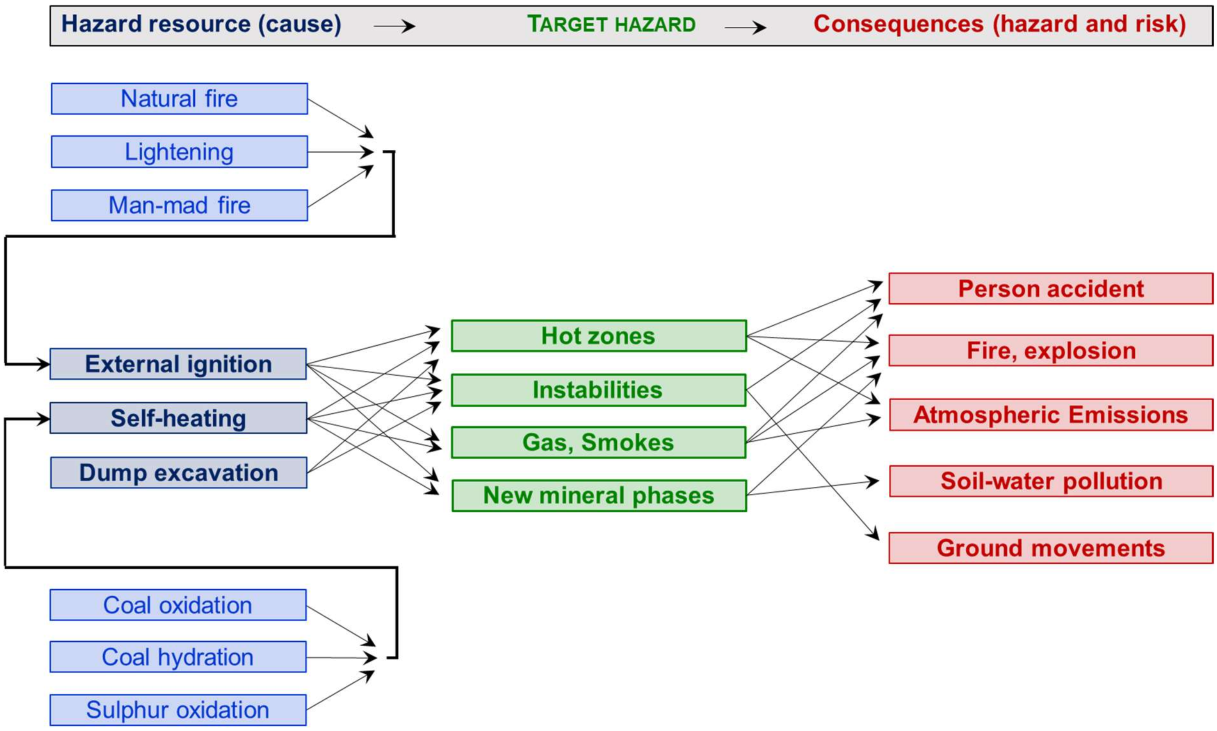


Figure 12. Fire – self-heating (combustion) hazard and the potential interactions with natural, mining and technological hazards (Ineris, 2023)

- gas: this mining hazard can interact with two mining hazards:
  - gas-radioactivity (M4-M5): the mine gas hazard can modify the atmosphere conditions of mines. The gas hazard can aggravate the radioactivity production and trigger air pollution. This interaction can be a low interaction (GREEN).
  - gas- pollution (M4-M6): the mine gas hazard can modify the atmosphere conditions of mines. The gas hazard can aggravate air pollution. This interaction can be a high interaction (RED).

It has been noted that the gas, radioactivity, and pollution can interact together and create a potential impact.

4.3.2 Mining-natural hazard interaction

For studying the hazard interaction, six mining hazards and 6 natural hazards are selected based on the feedback and the potential interaction between the mining hazards and natural hazards. The interaction matrix is composed of 12*12 mining-natural hazards. In this case, theoretically, 144 potential bi-interactions should be studied to assess the potential and the level of the interactions (Figure 13). If we exclude the interaction between the natural-natural hazards, outside the scope of the PoMHaz project, the number of the potential bi-interactions is equal to 108.

Based on the expert feedback, additionally to the 12 mining-mining interactions, we can account for 27 potential interactions:

- For 9 cases, a mining hazard can trigger a natural hazard (e.g. the mining ground movement can trigger a ground movement such as sinkhole, landslide).

- For 18 cases, the double, a natural hazard can trigger a mining hazard (e.g. the natural ground movement can trigger a mining ground movement such as sinkhole, landslide).

The classification of the 27 interactions can be classified as following:

- In total, 14 cases present a high-level interaction (RED).
- 6 medium (moderate) level interaction (ORANGE).
- and 7 low interaction level (GREEN).

The following cases of interaction are identified for a natural hazard as a triggering hazard, the mining hazard as an aggravating hazard:

- flooding-ground movement: a massive and uncontrolled inflow of water, due to the collapse of a water reservoir or the main supply water network or/and the heavy rainfall, into the mines operated by room and pillar can induce the collapse of underground mine and which can consequently cause a ground movement (subsidence, landslide, etc.). A flooding of the mine can trigger or worsen the sinkhole-type terrain movement hazard. For example, an upwelling of underground water which contributes to the flooding of mining voids can cause land uplifts or lead to surface flooding, sloughing or progressive subsidence. This can also be a domino interaction or an aggravation of the ground movement hazard.
- drought-gas: a drought hazard may be related to hydrological and hydrogeological disturbances in mining reservoirs, and thus modifies the flow of gas into the surface. Additionally, intensive, or inadequate use of available water may have an influence on groundwater levels, which consequently causes ground movements on the surface in abandoned mine., The decline in mining water reservoirs may also cause the swelling shrinkage of clay soils.
- a runoff hazard can interact with a ground movement hazard: surface water runoff weakens land strength and promotes land failure by causing land collapses or settlements above old mining operations or deposits. The heavy rainfalls can be the cause of mine collapses, especially for works located at shallow depths.
- long-lasting rainfalls and violent thunderstorms can be at the origin of a significant flood or a slow rise of the water tables which can cause river overflows, which in turn can be spread by the hazard of runoff in urbanized areas.
- wildfires in abandoned wooded open-cast mines. These fires cause land movements, falling blocks and mud flows (sudden erosion of the soil in the event of precipitation, etc.).
- earthquakes, cyclones or torrential downpours can destabilize the slopes which in turn cause landslides (mines and slag heaps). Earthquakes can cause, but in a much rarer way, collapses of shallow mines operated by abandoned rooms and pillars (Lenhardt, 2009, Azhari and Ozbay, 2017). The slope instability of an open pit mine can be trigged by an earthquake where the focal is at a distance equal or less than 100 km and the magnitude is superior to 6.0.

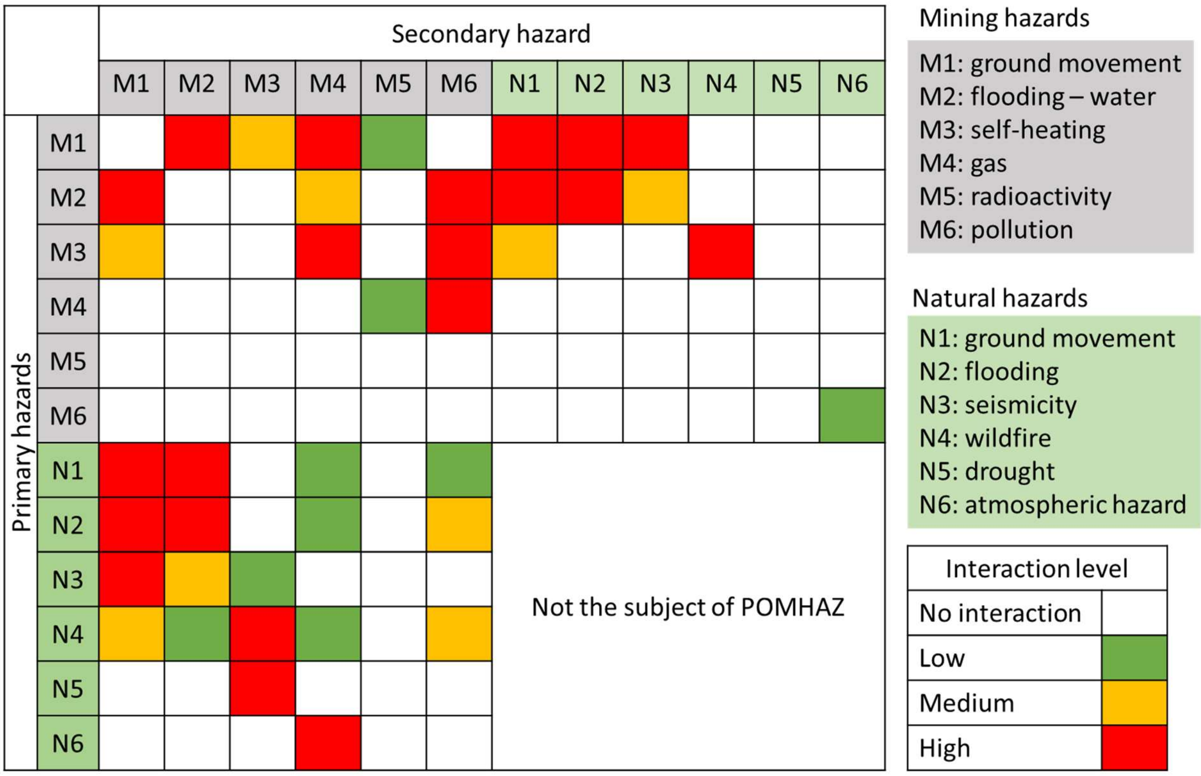


Figure 13. Interaction matrix between the main 6 mining hazards (M1 to M6) and 6 natural hazards (N1-N6).

4.3.3 Mining-technological hazard interaction

Technological hazards are regrouped in four groups and selected. They are selected based on the feedback and the potential interaction between the mining hazard and technological hazards.

The interaction matrix is composed of 10*10 mining-technological hazards. In this case, theoretically, 100 potential bi-interactions should be studied (Figure 14). If we exclude the interaction between the technological hazards, not included in the POMHAZ project, the number of the potential bi-interactions is equal to 64. Based on the expert feedback, additionally to the 12 mining-mining interactions, we can account for 23 potential interactions. For 11 cases, a mining hazard can trigger a technological hazard (e.g. the mining ground movement can trigger an infrastructure: sinkhole, landslide, etc.). For 12 cases, a technological hazard can trigger a mining hazard (e.g. the collapse of a water reservoir triggering a mining ground movement: sinkhole, landslide, etc.). In total, 11 cases present a high-level interaction, 9 medium (moderate) level interaction and 3 low interaction level.

The following cases of interaction are identified for the technological hazard as trigger hazard, mining hazard as aggravating hazard. Herein, some examples for which certain technological hazards can interact with the mining hazards:

- ground-movement-structure (M1-T4): the ground movement occurrence (general collapse, sinkhole, crevasse, etc.) can create large deferential settlement. Consequentially, the ground movement hazard can trigger the collapse of the infrastructure (e.g.: water supply, electrical network, etc.). This interaction corresponds to an aggravation of the infrastructure hazard. The level of the interaction can be considered as a high-level interaction and a cascading effect can occur.

- pollution-structure (M4-M6-T4): the air pollution by the dust/toxic gas hazard. Consequentially, the pollution can trigger the accidents of a critical infrastructure (e.g.: highway, etc.). This interaction corresponds to an aggravation of the infrastructure hazard. The level of the interaction can be considered as a high-level interaction and a cascading effect can be occur.
- overpressure ground movement (T3-M1): the failure of specific structures such as dams and sewerage or drinking water networks can directly trigger the flooding of abandoned mines and cause widespread or localized collapses.
- over-pressure-ground-movement (T3-M1): intensive agriculture like the large cereal farms, causes soil erosion, which can lead to mechanical instability of the soil such as flow, landslide of underground mining works.
- structure-ground movement (T4-M1): the rupture of exceptional bridges / viaducts can cause surface movements of land on the flanks / fronts of open-sky mines and cause underground disorders.
- thermal-overpressure (explosion) -ground movement (T1-T3-M1-M6): an explosion of an industrial site can cause mine ground movements and pollute the soil and groundwater. The consequences of an explosion occurrence (vibration, over-pressure, thermal, etc.) can create or increase the ground movement (sinkhole, landslide, etc.), and lead to transfer of pollution. This interaction corresponds to an aggravation of the ground-movement and mining pollution. The level of the interaction can be considered as a high-level interaction and a cascading effect can occur.

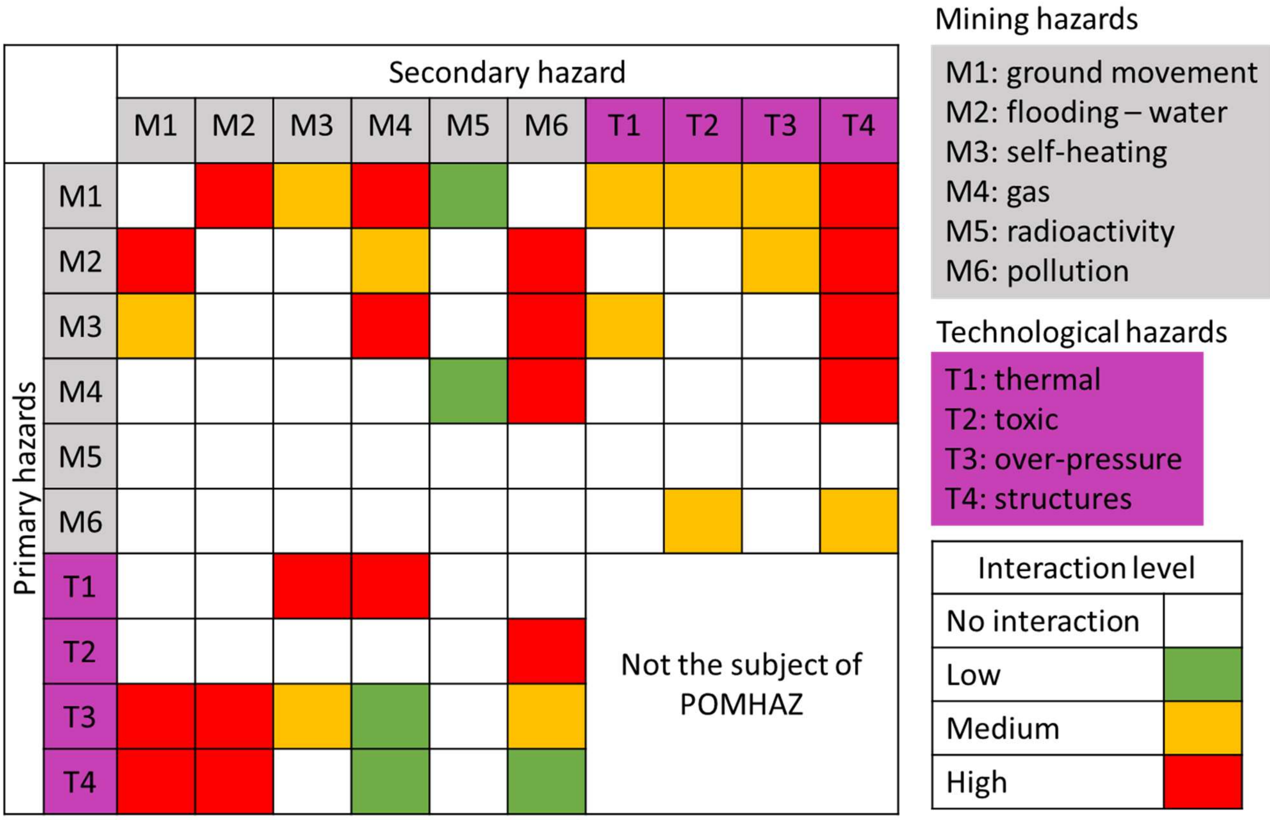


Figure 14. Interaction matrix between the main 6 mining hazards (M1 to M6) and 4 technological hazards (T1-T4).

4.4 Interaction diagrams

In the previous section, the matrix of interaction was used to identify the potential of the interaction between mining, natural and technological hazards. The matrix of interaction allows to identify the interaction between two hazards and hardly for several hazards and to build multi-hazard scenario. The interaction matrix can be constructed after carrying out a multi-hazard analysis. For instance, a mining hazard can induce a natural hazard, and consequently, the natural hazard can induce a technological hazard. Additionally, the external factors, such as overload, aging, traffic, etc., can play an immediate or differed role to trigger a hazard: mining, natural hazard.

The interaction diagram representation is based on physical rules and the mechanism underlying the event. They are a very powerful technique as it allows to extrapolate beyond the range of data, and it allows a physical justification of the interactions between events within the realm of the assumptions made to exemplify the phenomena.

The interaction diagram can be built to identify the potential interactions between mining-mining hazards, mining-natural hazards, and mining-natural-technological hazards. Based on the expert's knowledge, and the internal and external factors of the physical phenomenon, the interactions are qualified, so this is a qualitative method. The types of interactions are considered: direct simple interaction between two hazards (one way), double interaction (double way) and cascading effect (more than two hazards can be triggered at the same time and location). Additionally, the levels of the interaction are similar to the matrix of interaction: low, medium and high. The interaction diagram is carried out for the 17 individual mining hazards, that can be interacted with 14 natural hazards and 3 technological hazards.

To illustrate the complexity and the multiple-interaction possibilities, the Figure 15 presents the subsidence (sub), as a mining hazard, interacting with 9 mining hazards, 6 natural hazards and 2 technological hazards. Two external factors can play an important role and increase the probability of the occurrence: the traffic and the aging. The seismicity, flooding, overload, dam collapse, etc. can increase and aggravate the sinkhole hazard level directly or indirectly due to ageing phenomenon which decreases the strength of the geomaterial. The Figure 15also presents the type and the level of the interaction. One notices that 2 cascade interactions are identified, they present a high level of interaction.

Mining	SUB		CRE	SIN	MMC	SAT	DLS	SLS	ERO	MUF	RLS	RFA	GAS	COM	MWR	MOR	TFL	ISI
Natural	SUB	SIN	DIS	SAT	SAS	DLS	SLS	ERO		MUF	RLS	RFA	INU		WFI	NSI		
Tech	THER							TOX/POLL						SURP				

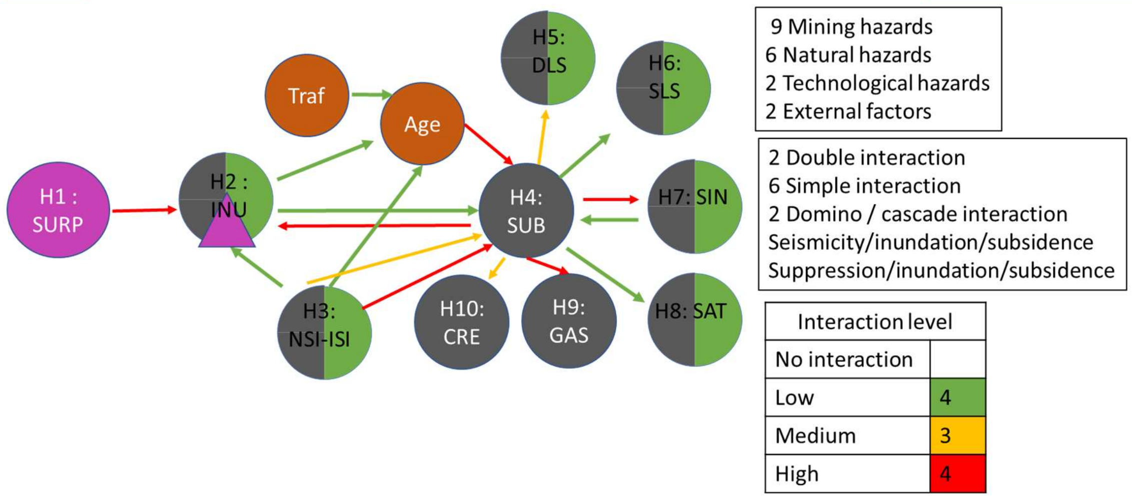


Figure 15. Diagram of hazard interaction (mining, natural and technological), the subsidence mining hazard is the target hazard, and the other hazards are the sources hazards.

The analysis carried out for the subsidence mining hazard is also carried out for the 17 mining hazards. They are presented in the annexe of the report. The Table 2 represents a synthesis of the interactions of the mining hazards, natural and technological hazards. One can notice that the flooding hazard (mining, natural and technological origins) has the maximum potential of interactions with the other hazards, with 23 potential interactions, 20 of them are judged as high-level interaction, that means the potential of the interaction is very serious and can increase the intensity and the severity of the individual hazards. Additionally, many cascading interactions can be created depending on the predisposition factors of the site. The second hazard presenting a high level of interactions is the sinkhole with 17 potential interactions.

Table 2. Synthesis of the interaction between mining hazards, natural and technological hazards (level and type of potential interaction)

Mining hazard	Total	Level of interaction			Type of the interaction		
		Low	Medium	High	Simple	Double	Cascade
Subsidence	11	4	3	4	7	2	2
Crevice	10	3	4	3	7	1	2
Sinkhole	17	6	4	7	4	6	7
Mass collapse	13	3	5	5	8	3	2
Settlement	6	5	0	1	4	1	1
Deep-seated landslide	8	1	2	5	4	3	1
Shallow landslide	10	6	1	3	4	3	2
Erosion	11	5	3	3	4	5	2
Mudflow	9	5	2	2	6	2	2
Rock fall/Rock slide	8	5	0	3	3	3	2
Gas	10	8	0	2	7	0	3
Combustion	9	6	3	0	5	2	3
Hydrology	8	1	4	3	5	1	2
Inundation	23	7	3	10	3	8	12
Induced seismicity	12	6	3	3	4	4	4

4.5 Temporal and spatial scales of hazards interactions

The interaction between mining, natural and technological hazards, depends on the scales: spatial scale and temporal scale.

Spatial scale is a specific application of the term scale for describing or categorizing (e.g. into orders of magnitude) the size of a space (hence spatial), or the extent of it at which a phenomenon or process occurs. The temporal scale is used to measure the change in a variable over time. Different phenomena are measured using different scales. Gill and Malamud (2014) used temporal and special scales to represent the interaction of natural hazards.

De Angeli et al. (2022) presented a frame of multi-hazard assessment based on the spatial and temporal interaction of two hazards (H1, H2). They identified four situations:

(i) temporal-spatial interaction, this corresponds to overlap of impact of hazards.

(ii) temporal but not spatial interaction, this has interaction between two hazards but the impact or the consequences are not in the same space.
(iii) spatial but not temporal interaction and
(iv) independent hazards.

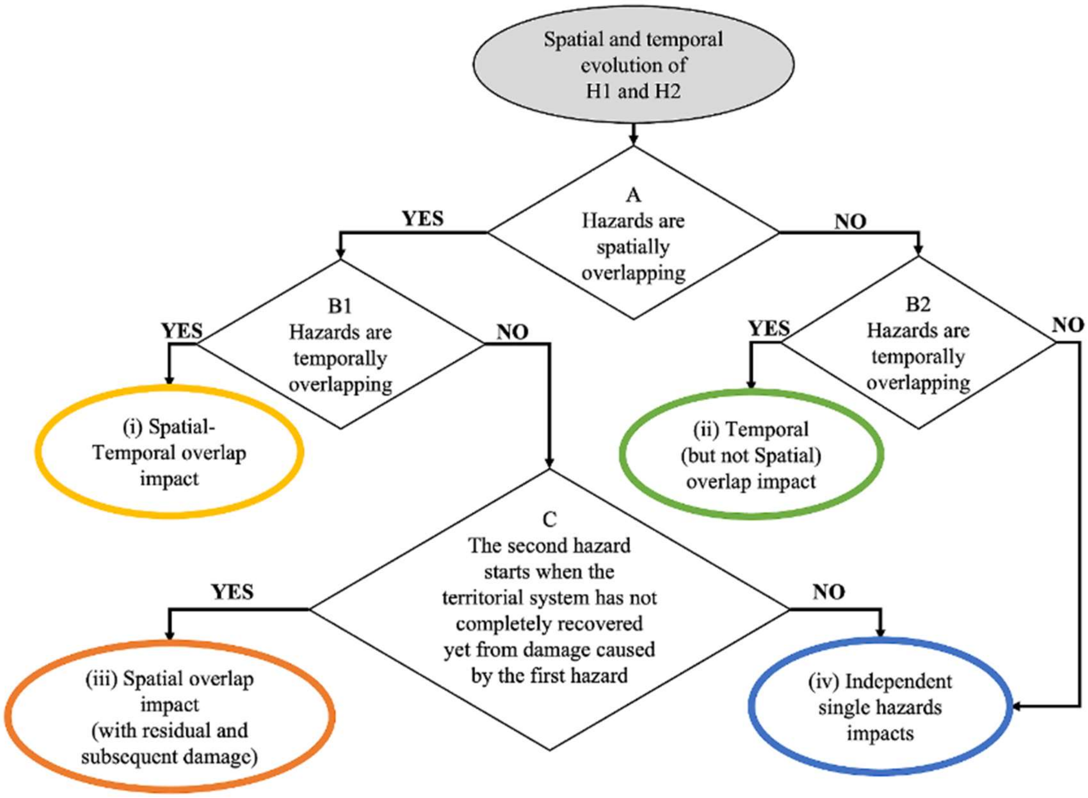


Figure 16. Identification of the temporal and spatial hazard interaction (De Angeli et al., 2022)

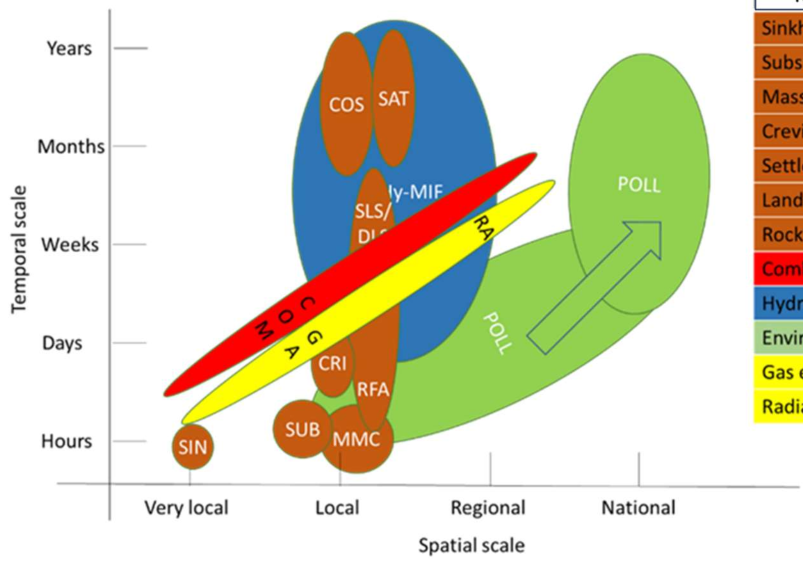
Based on the information obtained in the WP2 of the POMHAZ project and feedback from analysis, Ineris tried to build a scale diagram for mining and natural hazards. The Figure 17 represents the potential interaction of several mining-natural hazards using a temporal and spatial scale. In the case of mining and natural hazards, the spatial scale covers a very limited surface (very local) to a very large surface (regional land). The temporal scale covers a very short event, hours, to very a long period (years).

Certain mining hazards are very local and very short (e.g.: a sinkhole hazard, the occurrence in the surface), the interaction with another hazard may be limited even if the interaction is theoretically possible. The interaction between hazards should fulfil the following spatial and temporal conditions:

- the occurrence of the hazard H1 corresponds to the occurrence, in time and in space, to the occurrence of the hazard H2.
    - For instance, the flooding of a mining site, a large-scale site, can interact with the sinkhole hazard, if and only if the collapse of the cavity is imminent or can occur shortly. In this case, the level of the interaction between the two hazards can be considered as high.
- the occurrence of the H1 modify, over the time, the conditions of the occurrence of the H2.

- For instance, the flooding of the underground mine, can interact with aquifer and can remobilise or release contaminants which have impacts on the water quality. It can take years to observe such interaction.

In the other hand, certain hazards can concern a large surface (hectares) and can last a long time (years): self-fire or self-combustion of coal dump. Under specific condition, long drought period, the coal can start the self-heating. Thus, the self-heating hazard can trigger a pollution of water and air for a long distance, etc. In this example, it is very important to assess, not only the potential of the interaction, but also the scales of the interaction (spatial and temporal).



Mining-natural-Technological	
Sinkhole	SIN
Subsidence	SUB
Massive mine collapse	MMC
Crevice	CRE
Settlement	SAT
Landslide	SLS-DLS
Rock falls	RFA
Combustion – Self-heating	COM
Hydrological/hydrogeological	Hy-MIF
Environmental pollution	POLL
Gas emissions	GA
Radiation	RA

Figure 17. Mining hazard interaction over temporal and spatial scales.

Additionally, to the physical interactions between the mining, natural and technological hazards, a regulatory interaction can be identified. Different administrative and regulations rules exist for managing a single natural/technological and mining hazard. The different types of regulatory interactions that have been listed are as follows: independent; complementary; contradictory and incompatible. For example, it is strongly recommended to manage a single administrative document when several hazards may interact simplifying the application of the mitigation measurements and avoiding the conflict and the misunderstanding. The measures and constructive devices thus ensure a fairer protection and reduction of the stakes exposed to several hazards. Considering the regulatory interactions make the use of codes, services, and other regulatory tools easier to characterize and manage risks, particularly in terms of urban planning and constructive measures. The analysis of regulatory interactions makes it possible to reassess regulatory measures adapted to multi-hazard and to propose better solutions in the event of unresolved conflicts or unsuitable regulatory recommendations.

4.6 Mapping multi-hazard (MHM)

The main purpose of mapping the multi-hazard results MHM is to gather in one map the different hazard-related information for a study area to convey a composite picture of the hazards of varying magnitude, frequency, and area of effect (Oas, chapiter 6, 1991).

The methods of assessing mining, natural and technological hazards are different. However, there is no methodological framework of reference for multi-risk / multi-hazard analysis concerning the assessment of hazards of post- (abandoned) mines yet.

The mining hazard is qualified according to its intensity and the predisposition of the site studied. Three intensity classes are considered (limited; moderate and high) and three predisposition classes (not very sensitive, sensitive, and very sensitive). They allow to assess the hazards; either by prioritizing the damage or potential nuisances according to the nature of the phenomena or by analysing the possibility of the appearance or manifestation on the surface of a phenomenon.

The level of interaction between hazards is estimated from the factors determining their intensity on the one hand and their probability of occurrence on the other hand. For anthropogenic or natural geotechnical phenomena that are not repetitive, the probability of occurrence is replaced by the predisposition of the site to the occurrence of the phenomenon. Thus, the interactions between the identified hazards can be hierarchized in three levels, compared to a method described in the methodological guide for the development of Mining Risk Prevention Plans: high, medium and low.

Chang et al. (2022) studied a large mining area (several square km), where the instability of artificial slopes is increased due to rainfall infiltration. They combined different hazards: landslide, ground subsidence, rainfall, and debris flows. The rainfall is considered as the trigger hazard. Using GIS (Global Information System) techniques to map the multi-hazards and risk, considering the natural hazards (land slide, heavy rainfall), and the mine instability (slope). However, this study did not show the potential interaction between hazards.

Based on the approach presented by Liu et al. (2021) and the feedback from the evaluation and the assessment of the mining hazards, we consider three levels of potential interactions:

- the level of the interaction is low or absence of interaction: no potential for the interaction (temporal and spatial) for the existing identified hazards:
    - no modification of level of the hazard intensity.
- the level of the interaction is judged as medium level between the existing hazards (e.g.: the interaction between the subsidence and the flooding):
    - the initial hazard intensity will be increased, at least by one level,
- the level of the interaction is judged as high level between the existing hazards (e.g.: the interaction between the sinkhole and the flooding):
    - the initial hazard intensity will be increased, at least by one level or two level depending on the initial intensity levels of the interacted hazard,

Table 3presents a suggested approach to adjust the initial hazard level (intensity) based on the level of the interaction. The initial hazard level (intensity) is upgraded, at least one level. The new intensity can be mapped using the classical hazard mapping methods.

Table 3. Example of adjusted hazard level considering the multi-hazard analysis: hazard interaction

Initial hazard level	Interaction level	Adjusted hazard level
Low / Medium / High	Low / No interaction	Low / Medium / High
Low	Medium	Medium
Medium		High
High		High
Low	High	Medium
Medium		High
High		Very High

The multi-hazard intensity (MH) can be calculated after the adjustment of each single hazard as following:

$$MH = \sum_{1}^{n} H_{ad-i}$$

n: number of single hazards identified on the studied site.

H_{ad-I}: Adjusted intensity of the single hazard (H_i)

For instance: existing shallow mine presents a sinkhole hazard (mining hazard), the mine is in a flooding zone, the sinkhole can occur in the surface, after the inundation of the terrain (single or several times). The occurrence of the sinkhole will induce the collapse of the gas pipeline (technical hazard), following the collapse of the pipeline, a wildfire can be declared, the fire propagation will trigger another one, etc. To calculate the MH, we should replace the intensity scale, low, medium and high by equivalent scale for which each level is replaced by a number and each interaction level is replaced by a number. The result is an adjusted intensity level for the analysed hazard.

Liu et al. (2021) suggested a method presented in the previous deliverable (D7), based on the intensity degree and the level of the interaction:

- no interaction, no adjustment is necessary.
- high interaction level (cascading interaction), the adjustment factor depends on the intensity level of the initial intensity level.
    - high interaction: 3 factors (high, moderate, and low: 1.5, 1.4 and 1.3) can be used, they are function of the intensity degree of the primary hazard (1 to 5).
    - low interaction level, 3 factors (1.3, 1.2 and 1.1) can be used, they are function of the intensity degree of the primary hazard (1 to 5).

The previous approach based on the adjustment of the level of hazard and the level of interaction can be improved. Ineris adopted the same method for the mining-mining hazard interaction and mining-natural hazard interaction (Table 4). The mining-natural hazard interaction coefficient are bigger than mining-mining coefficient. The justification of this choice is based on the consequences of the impact of the natural hazards. For instance, the flooding due to the heavy rainfall is more important than the flooding due to the rising of the mining water, or the stopping of water pumping. The Table 4 represents the adopted coefficient following the level of the initial mining hazard intensity and the level of the interaction. Those coefficients can be modified for a specific context and based on the expert opinion of the local context.

Table 4. Adjusted coefficients of initial hazard due to their interaction with mining or natural hazards.

		Interaction Level	Coef/mining		Adjusted hazard (M-M)		
		low	1		1	1,1	1,2
		Moderate	1,1		1,2	1,32	1,44
Initial mining hazard		Severe	1,2		1,3	1,43	1,56
Low	1						
Moderate	1,2	Interaction Level	Coef/Nat		Adjusted hazard (M-N)		
Severe	1,3	low	1,2		1,2	1,3	1,5
		Moderate	1,3		1,56	1,56	1,8
		Severe	1,5		1,56	1,69	1,95

The following examples illustrate the calculation of the multi-hazard intensity (MH) for two cases of post-mining and natural hazard interaction.

$$MH = Had1 + Had2$$

First case:

The site presents two mining hazards:

H1: sinkhole (ground movement) with a moderate intensity level (H1=1.2).

H2: flooding hazard with a low intensity level (H2=1).

Based on the interaction matrix and diagram, the interaction level between the two mining hazards can be considered as severe, thus the adjusted intensities for H1 and H2 are:

H_{ad1} = 1.2*1.2=1.44 and the

H_{ad2}=1.2*1=1.2

Finally the MH (1,2)=1.44+1.2=2.46

Second case:

The site presents two hazards, mining and natural hazards:

H1: sinkhole is mining hazard with a moderate level (H1=1.2).

H2: flooding is natural hazard with a low level (H2=1).

The interaction level between the two mining hazards can be considered as severe, thus the adjusted intensity: H_{ad1} = 1.5*1.2=1. 8 and the H_{ad2}=1.5*1=1.5

Finally the MH (1.2)=1.8+1.5=3.3

Thanks to the suggested methodology, the results highlight that the natural hazard flooding presents a greater impact, relatively to the mining hazard flooding (the ratio is equal to 35%). The calculation of the multi-hazard intensity (MH) can present a large interest in terms of multi-hazard intensity mapping.

4.7 Conclusion

The assessment of the potential interactions of mining hazards with natural and technological hazards is very important for the management of the abandoned mining sites in Europe and all over the world. The work done, in this task of the work package (WP2), concerned the development of the interaction tools: matrix of interaction, interaction diagrams. These are qualitative approaches. The identification of the potential interactions between hazards are based on the partners knowledge, as experts of the mining, natural and technological hazards. The methodology of the multi-hazard for mining sites consists of three main steps:

- first identification of the main mining, natural and technological hazards,
- second, the identification of the potential interaction based on the internal predisposition factors and external factors,
- third, the identification of the type and the level of the interaction. Three types of interactions were adopted: simple, double and cascading (domino). Three levels of interaction were also adopted: low (green), moderate (orange) and severe (red).
- fourth, the calculation of the MH intensity, the calculation was developed taking into consideration the level of the initial hazard, the level of the interaction and the number of the existing hazards.

The application of the developed methodology needs a large effort for collecting the different information firstly to assess the level of the single hazards and then to build the matrix of interactions or the diagrams of interactions. Additionally, different scenarios can be (should) identified, described, allowing measuring the probability of occurrence for a specific site.

5 Example of hazard interactions

In this section, we present several examples concerning the mining hazard interactions (mining-mining hazards, mining-natural hazards, etc.), in the frame of abandoned mines:

Tailing dams collapse – earthquake

The earthquake is a natural hazard which can interact with collapse of waste dumps of mine. The earthquake can trigger the collapse of the deposit and the release of materials can pollute the water, etc. In 1928, an earthquake measuring 8.3 on the Richter scale occurred near the Barahona copper mine in Chile, causing a failure of the waste impoundment. Nearly 3 million cubic meters of toxic waste flowed down the valley, killing 54 people (ICOLD, 2001:110). Tailings impoundment design has improved considerably since the early days of industrial mining. However, accidents still occur with surprising frequency. According to a study by the International Council on Large Dams (ICOLD), about two mine structure accidents have occurred per year over the last 6 years (ICOLD, 2001:6). In the last 12 years, approximately 31 tailings incidents have been recorded, of which nearly 40 percent resulted in loss of life or property[3].

Flooding – slope stability: heavy rain, water level, dam collapse can flood abandoned mine site.

Aberfan disaster (Wales, 1966), this is an interesting example of the interaction between the heavy rainfall (natural hazard) triggering the slope instability of coalmine spoil (mining hazard). The landslide of the spoil happened after three weeks of heavy rainfall. Consequently, the tip was saturated, and the spoil became completely unstable. The consequence of this disaster was: 144 people died, including 112 children, when a colliery spoil tip collapsed and flowed down into the village. More recently, nearly 220 cases of failure have been recorded since the beginning of the 20th century (Franck, 2020). The analysis was carried out for failures before 2008, nearly half of the cases are linked to exceptional climatic events (Rico et al., 2008), as was the case in 1936 in Sardinia where a strong flood partially destroyed an old tailings dam (Cidu and Fanfani, 2002). Azam and Li (2010) highlighted that the failures of tailing dams due to exceptional rains have increased from 25% to 40% since 2000.

Flooding-sinkhole

Lecomte et al. (2014) mentioned the case of a shaft (coal mine) located at Tirphil, New Tredegar (England). The collapse of shaft was reported in November 2010. Due to water ingress from the culvert, the collapse grew, and the following morning was approximately 10 metres diameter, 15 metres deep and filled with water to approximately 4 metres from road level. The shaft is connected to water drainage of the site and that considered as the main cause of the shaft collapse.

The Figure 18 represents the results of the TEXMIN project, the interrelation between the occurrence of the sinkhole and rainfall in UK is clearly identified for three years (2014-2017).

[3] Calculation based on the number of metal and coal mine tailings incidents with recorded releases and known impacts. For a complete list see: UNEP (2002), "Chronology of Major Tailings Dam Failures," Available online at:http://www.antenna.nl/wise/uranium/mdaf.html. Last accessed June 5, 2003

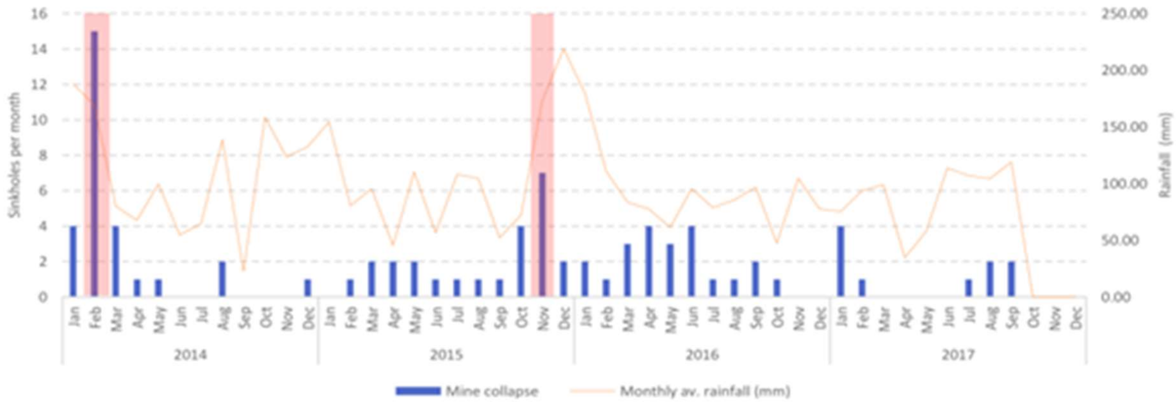


Figure 18. TEXMIN (RFCS project) – Correlation between sinkholes and rainfall in UK for 2014-2017

La Touche et al., (2018) represent a case study of the occurrence of a sinkhole due to multi-hazards: existing karst (natural cavities), mine flooding, and heavy rainfall. The heavy rainfall was considered as the trigged factor of the occurrence of a large sinkhole (14 m of diameter). Andreichuk et al. (2006) reported another case study regarding the interaction between mine flooding of a potassium underground mine and the formation of the large sinkhole (80 m of diameter), the heavy rainfall was the trigger factor (hazard).

Andreichuk et al. (2006) discussed the case of a large collapse of potassium mine, the large collapse happened because of the flooding of the mine despite its important depth, more than 400 m. In this case, the collapse hazard alone is null to very low. The flooding hazard is high due to water inflow through a fault, the influence of the flooding hazard, is high and the mine flooding triggers the collapse.

Natural and induce seismicity – mine collapse

Aydan and Tano, 2012 present the consequences of a strong earthquake in Japan (2011) with a moment magnitude of 9. They identified 316 sinkholes at shallow lignite coalmines. In this situation, the natural seismicity triggers the mine collapse, the interaction type is a domino because the collapse of the mines happened after the occurrence of the earthquake.

Ngcobo (2006) studied the interaction between three mining and natural hazards of a gold mine in South Africa. The flooding and dewatering of the mine can induce a sinkhole due to the collapse of the dolomite layer. The risk assessment carried out consider the role of the rainfall, the geology features, and the natural and induced seismic events. The conclusion of the work highlighted that the water pumping and natural seismicity trigger the collapse of the mining cavities. Additionally, they pointed that the sinkholes could generate a pollution risk associated with the sinkhole.

Donnelly (2006) mentioned the interaction between natural seismicity and the mining hazard (collapse of the underground structures). The reactivation of a fault though the last coal mine (Donetsk coal mining area, Ukraine) in the area was closed forty years ago. During coal mining, some accidents, such as coal-gas outburst, roof falling, and water were observed.

Subsidence – gas hazard

Lafortune et al. (2019) present the case study of the Lorraine coalmine where the production and the circulation of the gas ($C0_2$) interacted with two post-mine hazards: ground movement (subsidence: crevasses) and the flooding of the mine. They noticed that the gas circulation to the surface depends on the surface temperature. The circulation of the gas increases in the area of the crevices, due to the mining operations. Additionally, the flooding of the mine, due to the water pumping after the abandoned of the mine, changes the air pressure and plays a role on the gas emissions.

Forest fire-self-heating of coal dumps

Forest fires in Indonesia in 1997 and 1998 ignited hundreds of coal fires at outcrops (Brown, 2003). The self-heating of coal dumps produced hazardous elements like Pb, Cd, Zn, Hg, As. These elements migrate from the hot spots and enrich in the cooler surface in e.g. sulphide minerals as HgS. Different organic pollutants like phenols (originated from vitrinite particles), different PAHs with alkyl substitutes or oxidised PAHs, chlorinated PAHs, or sulphur heterocycles are also formed. Therefore, the high concentrations of PAHs and heavy metals in coal waste dumps represent a potential risk for human health due to their toxicity. Thus, as the self-heating hazard increases, it interacts with pollution due to the hazardous elements provided by the self-heating and those already present in dumps. This interaction was observed in several self-heating dumps in upper Salesian coal basin (Naduvari et al., 2021).

Recently, in the south of France (Hostens), a wildfire developed during the summer of 2022 when the temperature increased unusually during several months (July and August). In this zone, an abandoned shallow lignite open pit mine exists (Figure 19). The extraction of the lignite was stopped in 1964. The abandoned lignite mine is covered by different vegetations and becomes overtime as a public site.

The lignite layer presented a self-heating hazard. The drought period and the increasing of the soil temperature create the physical conditions for the self-heating of the lignite layer. Smoke emissions (air pollution) were observed due to the combustion of the lignite. At the same time, the self-heating created voids and cavities. The collapse of the voids created a large subsidence because the surface concerned by the event was very large. This case study illustrates the different types of interactions: cascading interaction: drought-self-heating-air pollution-subsidence and sinkhole (Figure 20). The subsidence and the sinkhole are new hazards initiated by the voids created by the self-heating.

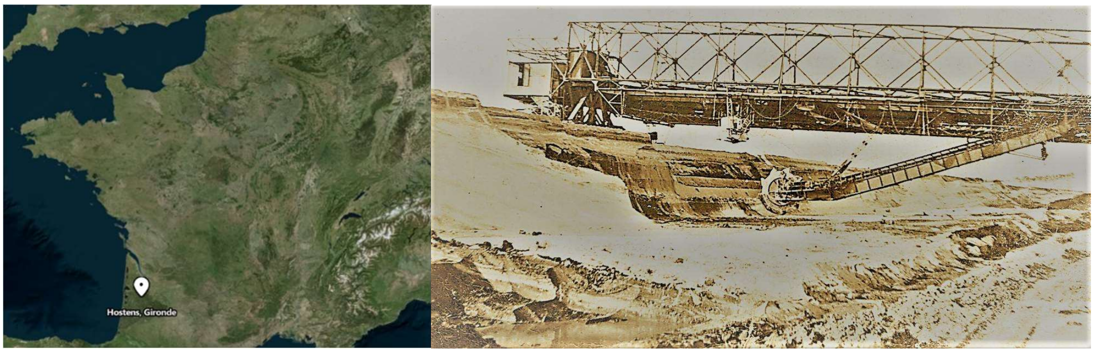


Figure 19. Abandoned lignite open-mine (Hostens – France)

Figure 20. Self-heating consequences of the open-pit abandoned lignite mine (France)

The Figure 21 presents the interaction between the thermal, wildfire (natural hazards) and the self-heating of the lignite mine. The self-heating trigger new mine hazards (subsidence and sinkhole) and pollution (air and water).

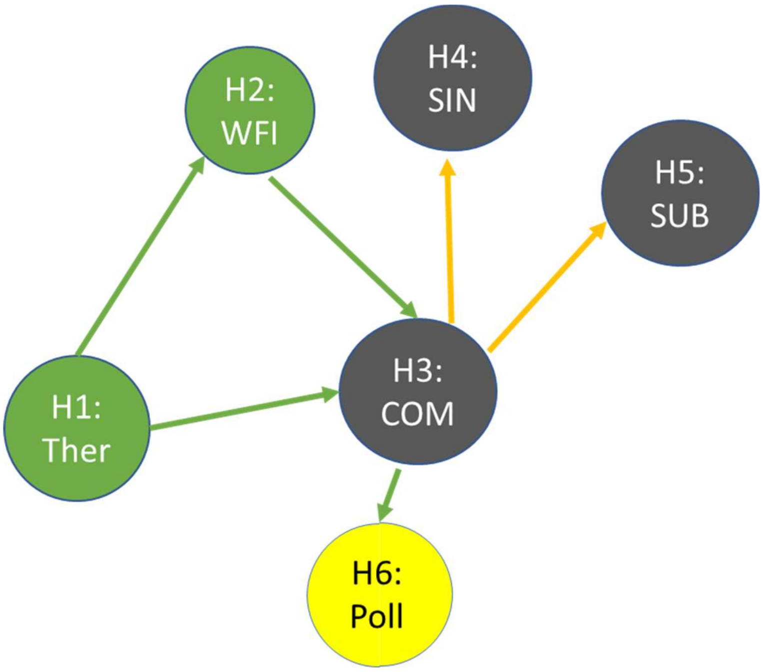


Figure 21. Interaction diagram of hazards related to the self-heating of Hostens lignite mine (France)

Additionally, Mavrommatis et al (2019) used multi-hazard and multi-risk methods to assess the interaction between mining activities and natural hazards related to climate change. They used Bayes theorem for considering the uncertainties. Valverde et al (2021) assessed the groundwater hazard for an underground coalmine in Spain considering the natural causes (Figure 22), technical causes and human causes. The different causes can impact the flows; however, they did not consider the interaction between the different causes (factors).

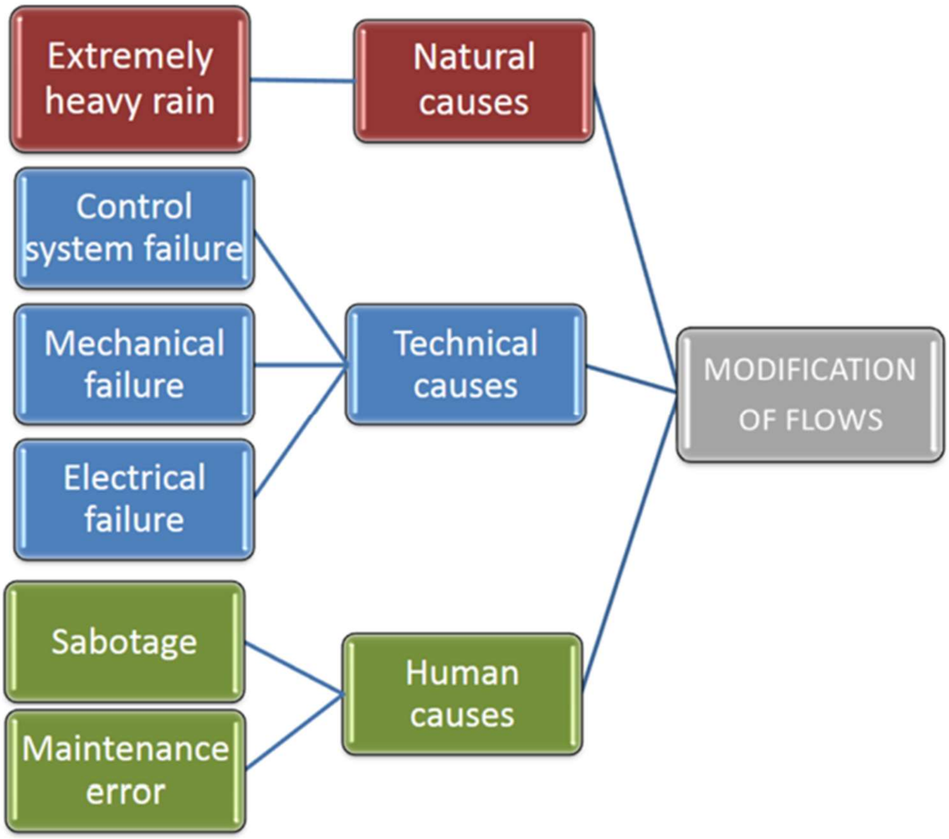


Figure 22. Tree formulation of the cause-and-effect analysis for the modification of flow effects (Valverde et al., 2021)

Ma et al, 2022 studied a surface multi-hazard related to underground coal-mine (China). The coal mine subsidence caused a mining induced landslide, and the landslide induced damages to lakes localised in the bottom-foot of the landslide zone (Figure 23).

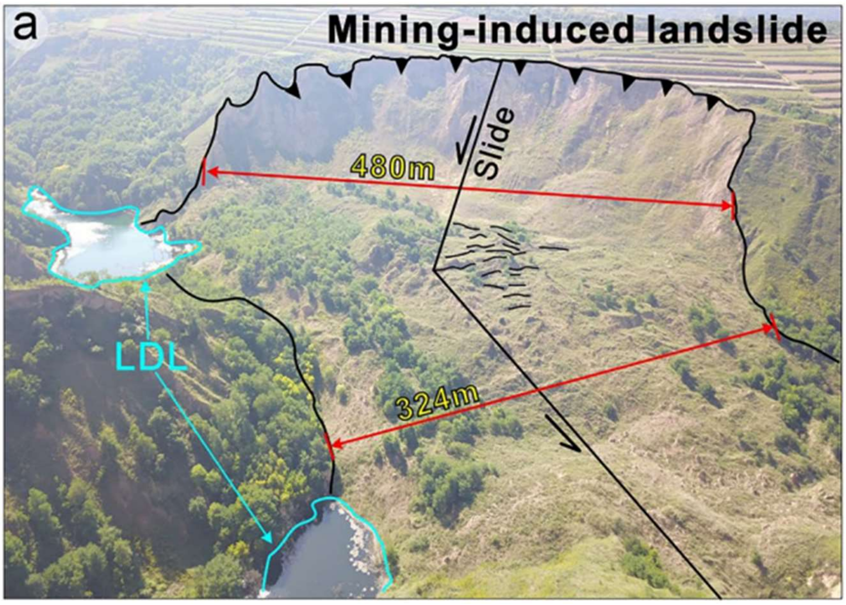


Figure 23. Example of the interaction between mining and natural hazards (Ma et al, 2022)

Fernandez et al. (2020) studied the relationship between a landslide and the underground subsidence induced by the underground coalmine in Spain.

Gerzsenyi and Albert (2021) presented a case study (Hungry) concerning the interaction between landslide and the waste mining installation (dump and heaps). The analysis is based on different factors (morphology, geology, etc.), the results of the analysis allowing mapping a unique multi-hazard map.

In conclusion, the examples presented in this chapiter confirm the interaction between hazards and their consequences. The consequences can be very severe when the two or more hazards can occur at the same time and the same place.

6 Application of the methodology on a case study

The case study concerns a former lignite coal mine in the south of France. The depth of the mining works is between 0 and 800 m, with several shallow mines (10 m - 140 m). Near the surface, additionally to the lignite mine, there is an underground limestone mine. The risk assessment studies carried out after the end of the mining activities identified several hazards; they can be grouped as follows:

• Mining hazards: ground movements (subsidence and landslide); flooding, self-heating.

• Natural hazards: wildfire; flood; natural seismicity; land movements (subsidence and collapses associated with underground cavities, landslide - rock and boulder falls and landslides).

• Technological hazards: transport of dangerous goods.

The following mining ground movements hazards were assessed: localized collapse, subsidence, landslide and settlement:

• localized collapse (sinkhole): the hazard level is between "low" and "medium".

• subsidence: the hazard level is between "medium brittle subsidence" and "weak flexible subsidence".

• landslide: the hazard of the landslide of the slag heaps is of "low" level with an intensity between "very limited" and "limited".

• settlement: the hazard is localized to the right of each slag heap; it was qualified as low with not very sensitive and a limited intensity.

The self-heating hazard of the slag heaps “low to medium” level hazard was only retained on outcrop zones. The presence of mining works is proven or supposed to be given that the presence of mining works can catalyse and worsen this phenomenon. This hazard could trigger a wildfire hazard.

The flood hazard relating to the modification of the regime at the level of four emergences was assessed as "low", and the so-called "brutal" flood hazard was assessed from "weak to strong". This hazard relates to the significant inflow of water into the drainage and water collection systems of the most sensitive slag heaps.

Regarding the natural hazards where several hazards have been identified: wildfire; flood; natural seismicity; ground movements (subsidence and collapses linked to underground cavities, landslide - rock and boulder falls and landslides) and bank erosion. They concern the phenomenon of shrinkage / swelling of clays and collapses linked to the presence of underground cavities (excluding mines).

Localized collapse: the land located directly above or in the immediate vicinity of old underground operations (limestone mines) correspond to a "strong" hazard level, while the surface land not directly under-mined but located at the edge of the farm corresponds to a" low "hazard level.

The level of the clay shrinkage-swelling hazard is important in the region, since the level of the hazard varies between "medium" and "strong". The natural seismicity is low to moderate in the north of the basin.

The Table 5 presents the different identified hazards (mining and natural hazards) as well as the intensity level. The mining hazards are mostly low to medium level, while the natural hazards are qualified as medium to very severe. The Figure 7 shows clearly the existence of multi-hazards in the mining area. Thus, it is necessary to assess the different mine-mine hazard and mine-natural hazard interactions.

<table>
<tr><th colspan="2">Hazard</th><th>Low</th><th>Medium</th><th>Severe</th><th>Very severe</th></tr>
<tr><td rowspan="7">Mine hazards</td><td>Ground movement – Sinkhole</td><td style="background:#FFE699"></td><td style="background:#FFE699"></td><td></td><td></td></tr>
<tr><td>Ground movement – Subsidence</td><td style="background:#FFE699"></td><td style="background:#FFE699"></td><td></td><td></td></tr>
<tr><td>Ground movement – Landslide</td><td style="background:#FFE699"></td><td></td><td></td><td></td></tr>
<tr><td>Ground movement – Settlement</td><td style="background:#FFE699"></td><td></td><td></td><td></td></tr>
<tr><td>Heating – Fire</td><td style="background:#FFE699"></td><td style="background:#FFE699"></td><td></td><td></td></tr>
<tr><td>Flooding</td><td style="background:#FFE699"></td><td></td><td></td><td></td></tr>
<tr><td>Induced seismicity</td><td style="background:#FFE699"></td><td style="background:#FFE699"></td><td></td><td></td></tr>
<tr><td rowspan="5">Natural hazards</td><td>Ground movement – Sinkhole</td><td style="background:#FFE699"></td><td></td><td></td><td style="background:#FFE699"></td></tr>
<tr><td>Ground movement – clay shrinkage – swelling</td><td></td><td style="background:#FFE699"></td><td style="background:#FFE699"></td><td></td></tr>
<tr><td>Natural seismicity</td><td></td><td style="background:#FFE699"></td><td></td><td></td></tr>
<tr><td>Flooding</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Wildfire</td><td></td><td></td><td></td><td></td></tr>
</table>

Table 5. Lignite mine - intensity level of the natural and mining hazards

The matrix of the interaction was built based on the assessment of the factor of each hazard (Table 6). Based on the collected information, three types of physical interaction were identified: between two or more natural hazards, between two hazards or more natural and "natural or man-made cavities outside mines" hazard and between two hazards or more natural and underground or open pit. For each interaction, the following configurations were considered: no interaction possible, only physical interaction, only regulatory interaction, and both physical and regulatory interaction. We note that this last type of interaction mainly concerns ground movements. The following observations can be summarized:

The flooding hazard due to the mining activity or the natural flooding (e.g. heavy raining) can be a trigger for several mining hazards. The flooding and the water fluctuation can increase the ground movements intensity or level, decrease the strength parameters, and mobilize the faults and discontinuity displacement. The natural seismicity and the flooding hazard can both increase the occurrence and the level of the ground movement hazard in the mining area. The natural seismicity and flooding can occur at the same time and the same area where shallow cavities (limestone mine) and coalmine exist, and they are characterized by a high to a medium level of ground movement hazard (sinkhole). In this case study, the multi-hazard analysis leads to increase the initial level of mining hazards. Furthermore, the occurrence of the natural hazards (flooding, natural seismicity, and collapse of the limestone mines) and the mining hazards (flooding and the collapse of the coalmine galleries, subsidence) correspond to a cascade scenario and thus cascade interaction. The likelihood of cascade scenario is relatively low.

Source hazard	Trigger hazards						
	Ground movement - Sinkhole	Ground movement - Subsidence	Ground movement - Landslide	Ground movement - Settlement	Heating - fire	Flooding	Induced seismicity
Mining (source) – mining (trigger) hazard interaction							
Ground movement - Sinkhole		Red	Yellow	Red		Red	Yellow
Ground movement - Subsidence	Yellow		Yellow	Red	Yellow	Red	Red
Ground movement - Landslide	Yellow	Yellow		Yellow	Yellow	Red	Green
Ground movement – Settlement	Green	Green	Green		Green	Green	Green
Heating – Fire	Green	Yellow	Red	Yellow		Green	Green
Flooding	Red	Red	Red	Red	Red		Red
Induced seismicity	Yellow	Yellow	Yellow	Yellow	Green	Green	
Mining (source) – natural hazard (trigger) interaction							
Ground movement - Sinkhole	Red	Red	Red	Red	Green	Yellow	Yellow
Ground movement – clay shrinkage – swelling	Green	Green	Green	Yellow	Green	Green	Green
Natural seismicity	Yellow	Yellow	Yellow	Red	Red	Red	Red
Flooding	Red	Red	Red	Red	Red	Red	Red
Forest fire	Green	Green	Green	Green	Red	Green	Green

Table 6. Lignite mine -multi-hazards interaction matrix and assessment of the level of the interaction: red: high, yellow: medium, green: low

7 Conclusion

This document presented the development of multi-hazards interaction and assessment in former abandoned mines. The objective was to:

- take stock of the consideration of the physical interactions between various hazardous phenomena and any regulatory incompatibilities or constructive provisions inherent in multi-risk. propose a methodology of multi-hazard assessment that considers the interactions between hazards around abandoned mines.

The Figure 24 presents the main steps, five in total, to carry out the multi-hazard assessment of post-mine hazards. The main steps are the following:

- the identification of the interaction between the hazards: mining, natural and technological hazards.
- the calculation of the multi-hazard index can be done automatically or manually using an Excel sheet.
- the application of the methodology in the project allowing to judge its advantages and its limitations in the post-mining context.

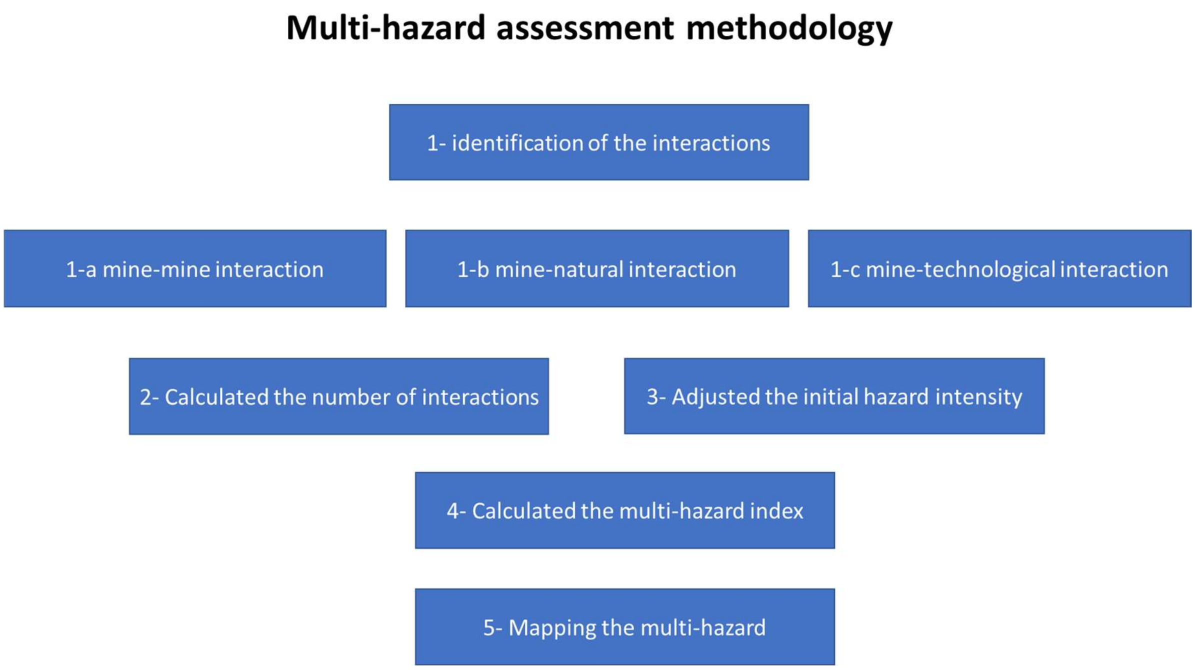


Figure 24. Suggested methodology to assess the multi-hazard interaction in the post-mining land

After recalling the advantages of this multi-hazard analysis, the work consisted of, on the one hand, describing in an almost exhaustive manner the three major families of hazards: mining hazards, natural hazards and technological hazards. Then, this involves describing the possible interactions between hazards according to their characters (trigger or aggravating); their categories (technical or regulatory), their typologies (dependent or independent). Finally, an attempt to assess the type and intensity of interactions between hazards has been proposed. This assessment, which is still under development, focuses on the analysis of possible interactions between hazards (mining, natural and technological), the possible combinations of several hazards, or the chain effect or the domino effect. The multi-hazard assessment methodology was applied on a lignite coalmine and showed the complexity and the utility for carrying out a such a risk assessment analysis improving the risk management in former abandoned mines.

8 Glossary

Heap leach: Using chemicals to dissolve minerals or metals out of an ore spread out as a lined/impervious pad. The solution percolates through the crushed ore, leaching out the ore.

Mine waste facilities: General term for installations designed and constructed for the storage of wastes generated by mining and processing activities, including tailings facilities, waste rock facilities, spent heap leach piles, slag heaps and process residues. Does not include domestic landfills or non-mining hazardous waste areas.

Tailings storage facility: Area where tailings are stored. Typically, a permanent facility. Facilities may include dams or other structures to retain tailings. Also called tailings landforms, tailings impoundments, tailings management facilities and integrated tailings facilities.

Heating and self-heating: The phenomenon of heating of coal deposits or slag heaps can be triggered spontaneously (self-heating) or provoked by contact with open fires on the right of the slag heap or deposit (natural forest fires, burnouts…).

In the first case, it is a phenomenon of combustion of the coal following the exothermic reaction of the oxidation of sulphides (pyrite) present within the materials by venting. This spontaneous triggering of combustion generally takes place shortly (a few months to a few years) after the disposal of waste rock coal or more rarely and later (no case listed in the basin of Provence), in contact with significant solar thermal radiation over a prolonged exposure period (drought). The burnt materials are then transformed into lime.

In the second case, the phenomenon is caused by an external event coming disturb the “state of thermal equilibrium” of the materials in the slag heap. The triggering of the combustion can be linked either to exposure to open fires of carbonaceous materials still present in the slag heap following natural or anthropogenic forest fires (burning, etc.) or by venting unburnt materials following phenomena of landslides or during earthworks. If the oxygen supply is sufficient, the combustion can then spread deep into the slag heap, preferentially following the most carbonaceous "layers".

9 References

Abdul-Wahed M.K., Al Heib M., Senfaute G. (2006). Mining-induced seismicity: seismic measurement using multiplet approach and numerical modelling. International Journal of Coal Geology, vol. 66, pp. 137-147.

Al Heib M., Nicolas M., Noirel J.F., Wojtkowiak F. (2005). Residual subsidence analysis after the end of coalmine work. Post-Mining 2005, November 16-17, Nancy, France. https://inis.iaea.org/collection/NCLCollectionStore/_Public/38/027/38027824.pdf.

Aldridge T., Gunawan O., Cruse H., Donald K., Roche N., Munday M. (2016). Modelling the Human and Economic Costs of Major Industrial Accidents. Hazards 26. Symposium n° 161. 11P.

Andreichuk V., A. Eraso A. and Dominguez M.C. (2006). A large sinkhole in the Verchekamsky potash in the Urals. IMWA. www.IMWA.info.

Aydan O. and Tano H. (2012). Sinkholes and subsidence above abandoned mines and quarries caused by the great east Japan earthquake on March 11, 2011 and their implications. Journal of Japan Association for Earthquake Engineering, Vol.12, No.4 (Special Issue).

Azam S., Li Q, (2010). Tailings Dam Failures: A Review of the Last One Hundred Years. Waste Geotechnics, Geotechnical News (2010): 50-53.

Azharia A., Ozbay U. (2017). Investigating the effect of earthquakes on open pit mine slopes. International Journal of Rock Mechanics and Mining Sciences. 100 218-228.

Bétournay M. C. (2009). Abandoned metal mine stability risk evaluation. Risk analysis vol. 29 N0. 10. DOI: 10.1111/j.1539-6924.2009.01267. pp. 1355-1370.

Brown, K., Subterranean Coal Fires Spark Disaster, Science, 2003:299:1177.

Camm T. and Girard-Dwyer J. (2000). Economic consequences of mining injuries. National Institute for Occupational Safety and Health, Spokane Research Laboratory, 315 E. Montgomery Ave., Spokane, WA 99207.

Chang M. Dou X. Tang L and Xu H. (2022). Risk assessment of multi-disaster in mining area of Guizhou, China. International Journal of disaster risk reduction 78 (2022) 103128. https://doi.org/10.1016/j.ijdrr.2022.103128.

Cidu R, Biddau R, Secci G, (2005). Legacy at abandoned mines: impact of mine wastes on surface waters. 9th International Mine Water Association Congress, Oviedo, Spain 2005: 247-252, https://www.imwa.info/docs/imwa_2005/IMWA2005_035_Cidu.pdf (consulté le 12/05/2020).

Donnelly L. J. (2006). A review of coal mining induced fault reactivation in Great Britain, Quarterly Journal of Engineering Geology and Hydrogeology, 39 (2006): 5-50

Durham, K., "Treating the risks in Cairns", Nat. Hazards 30(2), 251-261, 2003.

El Shayeb Y., Al Heib M., Josien J-P. (2004). Back analysis for predicting type and size of subsidence hazard over abandoned Lorraine iron mines. 32 International geological Congress, Aug 2004, Florence, Italy.

Eshrati L., Mahmoudzadeh A., Taghvaei M. (2015). Multi hazards risk assessment, a new methodology. International journal of health and disaster management. Vol. 3, Issue 2.

European commission (2010). Risk assessment and mapping guidelines for disaster management. SEC (2010) 1626 final. 43 p.

Fernandez P R., Granda G R, Krzemien A., Cortés S G, Valverde G F. (2020). Subsidence versus natural landslides when dealing with property damage liabilities in underground coal mines. International Journal of Rock Mechanics and Mining Sciences 126 (2020) 104175.

Franck C., (2020). Mouvement de terrain de type coulée lié aux ruptures de barrages de résidus miniers : retour d'expérience et évaluation du phénomène. Rapport Ineris - 178736 – 1971292.

Garcia-Aristizabal, A., P. Gasparini, and G. Uhinga (2015). Multi-risk assessment as a tool for decision-making. Future Cities, 4 (Climate change and urban vulnerability in Africa, Pauleit et al., Eds.), pp 229-258. doi: 10.1007/978-3-319-03982-4_7.

Gerzsenyi D. and Alber G. (2021). Geological hazards of the Gerecse Hills (Hungry). Journal of maps. 2021, VOL. 17, NO. 2, 730–740https://doi.org/10.1080/17445647.2021.2003259.

Gill J.C., Malamud B.D. (2014). Reviewing and visualizing the interactions of natural hazards, Rev. Geophys., 52, 680–722, doi:10.1002/2013RG000445.

Ineris (2017). Aléa versant rocheux sous-cavé. Caractérisation et évaluation. Ineris 17-164712-08773A.

Ineris (2023), Etat des lieux à l'international de la problématique des échauffements de terrils, Verneuil-en-Halatte : Ineris - 206841 - v2.0.

John A. (2021). Monitoring of Ground Movements Due to Mine Water Rise Using Satellite-Based Radar Interferometry—A Comprehensive Case Study for Low Movement Rates in the German Mining Area Lugau/Oelsnitz" Mining 1, no. 1: 35-58. https://doi.org/10.3390/mining1010004.

ISRM (2008). Mine closure and Post-mining management international state-of-the-art. https://www.ineris.fr/sites/ineris.fr/files/contribution/Documents/CDi_mineclosure_29_11_08-ang.pdf.

Kappes M.S. Keiler M., von Elverfeldt K. (2012). Challenges of analyzing multi-hazard risk: a review. Nat Hazards. 64:1925-1958. Doi 10.1007/s11069-012-0294-2.

Kappes M.S., Gruber K., Frigerio S., Bell R., Keiler M., Glade T. (2012). The MultiRISK platform: The technical concept and application of a regional-scale multihazard exposure analysis tool. Geomorphology 151-152, 139-155.

Krzemie ´n, A.; Sánchez, A.S.; Fernández, P.R.; Zimmermann, K.; Coto, F.G. Towards sustainability in underground coal mine closure contexts: A methodology proposal for environmental risk management. J. Clean. Prod. 2016, 139, 1044–1056. [CrossRef]

Lafortune S., Pokryszka Z., Charmoille A. (2019). Underground gas production and migration induced by mining subsidence. 14th International Congress of rock mechanics and rocks engineering.

Lagny C., Salmon R., Pokryszka Z., Lafortune S. (2012). Impact of mine closure and access facilities on gas emissions from old mine workings to surface: examples of French iron and coal Lorraine basins. 3. International Conference on Shaft Design and Construction (SDC 2012), Apr. 2012, London, United Kingdom.

La Touche G D, Balding B, Keenan B, La Touche S D (2018). Sinkhole development on mine flooding. 11th ICARD | IMWA | MWD Conference – "Risk to Opportunity". Pp. 585-590.

Lazar M., Nyari I-M., Faur F. G. (2015). Methodology for assessing the environmental risk due to mining waste dumps sliding – case study of Jiu valley. Carpathian Journal of Earth and Environmental Sciences.

Lecomte A., Salmon R., Yang W., Marshall A., Purvis M., et al. (2012). Case studies and analysis of mine shafts incidents in Europe. 3. International Conference on Shaft Design and Construction, Londres, United Kingdom.

Lenhardt W. A. (2009). The impact of earthquakes on mining operations. BHM, 154. Heft 6. Pp. 234-239.

Liu B., Han X., Qin L., Xu W., Fan J. (2021). Multi-hazard risk mapping for coupling of natural and technological hazards, Geomatics, Natural Hazards and Risk, 12:1, 2544-2560, DOI: 10.1080/19475705.2021.1969451.

Ma Sh., Qiu H. Yang·D., Wang ·J., Zhu·Y., Tang·B. Sun K.·Cao M., (2022). Surface multi-hazard effect of underground coal mining. Landslides DOI 10.1007/s10346-022-01961-0

Mavrommatis A., Damigos D., Mirasgedis S. (2019). Towards a comprehensive framework for climate change multi-risk assessment in the mining industry. Infrastructures 2019, 4, 38; doi:10.3390/infrastructures4030038 www.mdpi.com/journal/infrastructures.

Morgan A.J., and Dobson R., (2020). An analysis of water risk in the mining sector. Water Risk Filter Research Series Volume 1, WWF.

Mutke G., Bukowski P. (2011). Diagnosis of some hazards associated closuring of mines In Upper Silesia Coal Basin – Poland. Conference Proceedings of 11th International Multidisciplinary Scientific Geoconference SGEM 2011: Modern Management of Mine Producing, Geology and Environmental Protection. Bulgaria 2011. Vol 1, pp. 429-436.

Naduvari A., Abramowicz A. Ciesielczuk J. Cabala J., Kennan M. and Fabianska M. (2021). Self-heating coal waste fire monitoring and related environmental problems: case studies from Pland and Ukraine. Journal of Environmental geography 14 (3-4), 26-38. DOI: 10.2478/ /jengeo-2021-0009.

Ngcobo T.A. (2006). The risks associated with mines in dolomitic compartments. The Journal of The South African Institute of Mining and Metallurgy Vol. 106. Pp. 251-264.

OECD (2022). The impact of Natural hazards on hazardous installations. oe.cd/natech. 18 p.

OAS, Organization of American State (1991). Primer on natural hzard management in integrated development planning. https://www.oas.org/dsd/publications/unit/oea66e/begin.htm#Contents.

Rico M, Benito G, Salgueiro AR, Diez-Herrero A, Pereira HG, (2008). Reported tailings dam failures. A review of the European incidents in the worldwide concept. Journal of Hazardous Materials 152: 846-852, doi: 10.1016/j.hazmat.2007.07.050.

Spanidis, P.-M., Roumpos, C., Pavloudakis, F. (2019). A Methodology for Natural Hazards Risk Management in Continuous Surface Lignite Mines. Proceedings, 2nd International Conference on

UNDRR (2020). Hazard definition and classification review. Technical report. Sendai framework. 88 P.

Unger C. J., Everingham J-A. (2019). Reliable mine rehabilitation and closure to minimise residual risk. Abstract 76 - IAIA2019 Brisbane– Impact assessment of Project closure: meeting the new expectations.

UNISDR [2016]. Terminology for disaster risk reduction [ERMINOLOGY FOR DISASTER RISK REDUCTION, UNISDR. Available from: HTTPS://WWW.UNISDR.ORG/WE/INFORM/TERMINOLOGY

Valverde, F. G.; Duda, A.; Rodríguez, I. F.J.; Frejowski, A., Todorov, I., (2021). Groundwater Risk Assessment in the Context of an Underground Coal Mine Closure and and Economic Evaluation of Proposed Treatments: A Case Study Energies, 14, 1671. https://doi.org/ 10.3390/en14061671.

Zeng B., Shi T., Chen Z., Xiang L., Xiang Sh., Yang M. (2018). Mechanism of groundwater inrush hazard caused by solution mining in a multilayered rock-salt-mining area: a case study in Tongbai, China. Nat. Hazards Earth Syst. Sci., 18, 79–90, https://doi.org/10.5194/nhess-18-79-

What is PoMHaz?

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

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

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

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

The PoMHaz Consortium

ΔEH Public Power Corporation

INERIS maîtriser le risque pour un développement durable

Technische Hochschule Georg Agricola

GIG National Research Institute

CERTH CENTRE FOR RESEARCH & TECHNOLOGY HELLAS

SRK S.A.

TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG The University of Resources. Since 1765.