Mine Closure 2023 - Behrooz Abbasi, Jeff Parshley, Andy Fourie & Mark Tibbett (eds)
© 2023 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-7-2
doi:10.36487/ACG_repo/2315_102

Post-mining risk management in France and multi-hazard approaches for coal mines

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Abstract

After centuries of intensive exploitation of its mineral resources, French mining sites have gradually closed. However, after mine-closure and during the "post-mining" phase, numerous residual hazards can occur — sometimes as soon as mining works stop, or later, such as: ground movement phenomena (subsidence, collapses), rising gas, irreversible disruptions in underground water circulation induced by mining can potentially cause disturbances, both in terms of water circulation (flooding in low areas, disruption of waterway flows) and water quality (pollution).

To manage hazards and risks associated with these undesirable events, the French State has several technical and regulatory tools at its disposal. These tools make it possible to compile the available knowledge on residual mining risks related to former mining sites for a given territory, to delimit the affected areas and to define the conditions of construction, occupation, and use of land as well as measures relating to the organization, use or exploitation of existing assets in a context of a sustainable land planning management.

This paper presents the methodology to assess the post-mining hazards assessment. The paper also focuses on the development of new methodology for multi-hazards analysis regarding post-mining, natural and technologic hazards. The methodology analyses the hazards interactions and consequences on the environment. The multi-hazards assessment methodology consists of three steps: the identification of the singles hazards, the identification of the hazard interactions and finally the identification of the level and the consequences of the interactions. The matrix tool and interaction organigrams are used to identify the potential interactions. Three levels of interaction are considered: simple interaction, double interaction and dominos or cascading interactions. The natural and mining flooding hazard seems as the main hazard that can trigger several mining hazards: such as ground movement (subsidence, landslide, gas production, etc.).

Keywords: *post-mining, multi-hazard, interaction, natural hazard, matrix, adjustment*

1 Introduction and objectives

The former mining sites are generally associated with several hazards and risks (Parry and Chiverrell, 2019). Thus, risk assessment and their management are a central objective of the mining industry, mining authorities and decision-makers. Thus, the post-mining risk assessment presents a challenge to be in line with the sustainable development of mining regions. Mine closure can result in hazards, such as ground movements, induced or natural seismicity, hydraulic perturbations, flooding events, dangerous or toxic gas emissions or releases of potentially dangerous chemical substances into the environment (Bell, F. G.; Donnelly, 2006; Didier, 2008). The assessment of the different hazards must consider the interaction between mining hazards, i.e. the influence of one hazard on others. Multi-risk assessment research started relatively recently, in the 1990s, around natural hazards such floods, earthquakes, landslides, volcanic eruptions, snow avalanches and their potential interactions over a territory (Gallina et al., 2016; Garcia et al., 2016, Komendantova et al, 2015; Garcia-Aristizabal et al., 2015). Multi-risk assessment is then developed as a decision-support tool for climate change and urban vulnerability (Garcia-Aristizabal et al., 2015). Therefore, the interest in multi-risk assessment increased in the last decades, especially when it comes to applications and initiatives to assess risks from different natural and anthropogenic hazard events (Gallina et al., 2016).
A new risk assessment discipline was developed in recent years concerning the interaction between natural

and technological hazards, so-called Natech, requiring a comprehensive understanding of the interdependencies of human, natural and technological hazards (Krausmann et al. 2016).

In the mining context, the risk and hazard assessment studies have focused on a single hazard than multi-hazards (El Shayeb et al., 2004; Al Heib et al., 2005, Abdul-Wahed et al, 2006; Morgan and Dobson, 2020 Zhao and Tang 2015). However, closed mining areas are generally not affected by a single mining or natural hazard, but two or more can act at the same time or consecutively (Merad et al., 2004, Lenhardt, 2009; Kim et al., Azhari et al., 2017, Mavrommatis et al., 2019). In this context, assessing a single hazard can be unmanageable when multiple hazards must be considered. Furthermore, in a post-mining context, a multi-hazard approach is not apparent: the available data for the different single hazards may refer to different spatial scales; comparisons, rankings and aggregations can be difficult; different specialised entities and experts need to collaborate.

The objective of this paper is to present the existing methodology used in France to assess a single mining hazard, then the approach used to identify the interaction between several hazards.

2 Definitions and methodology

The term multi-hazard refers to the existence and the occurrence of several hazards in the same territory. The multi-risk assessment objective is to better consider the consequences of the interaction between hazards and risks. Hence, it can lead to improve the management of mining operations by authorities, stockholders, and decision makers of mining regions. Delmonaco and al. (2006) define multi-hazard analysis as the ‘implementation of methodologies and approaches aimed at assessing and mapping the potential occurrence of different types of natural hazards in a given area’. The European Commission (2010) considers multi-hazard analysis as the probability of occurrence (the probability of occurrence can be used to quantify a specific hazard) of different hazards, either occurring at the same time or shortly following each other, because they are dependent on each other or because they are caused by the same triggering event, such as rainfall, earthquake hazard or merely threatening the same elements at risk without chronological coincidence.

Liu et al. (2015) proposed a three-level framework for multi-risk assessment that considers the possible risk interactions. The first level concerns the existing or not interaction between the identified hazards. The second level is a semi-quantitative analysis approach to determine whether a more detailed, quantitative assessment is needed. The third level of the methodology is a detailed quantitative multi-risk analysis.

In this context, a multi-hazard assessment should be adopted as risk assessment method. The available data for the different single hazards should be analysed; compared, ranked, and aggregated by experts to identify the potential interaction and the level of the interactions. Mavrommatis et al. (2019) present a comprehensive framework for multi-risk analysis of climate change and provide operational recommendations for managing the interaction between the mining industry and natural hazards related to climate change.

2.1 Advantages and limitations

The reason of the development of multi-hazard approach is to reduce the cost of hazards. Feedback from various European countries has shown that separate hazard management decreases the effectiveness of prevention, because it does not consider the effects of interactions between phenomena and the effects of hazard-risk interactions. It, therefore, appears more and more necessary to consider risks in a ’globa’ approach, whereas mine managers and local authorities often manage only single hazards. In principle, single-hazard approaches assess the hazards separately, which implies that the solutions provided for their management do not consider the other phenomena and are sometimes incompatible with them. When the analysis does not take into account the interdependencies between the hazards, the assessment presents tools of little relevance to managing complex risks likely to lead to regulatory contradictions. For a site exposed to several hazards, multi-hazard analyses, unlike single-hazard analyses, involve considering each hazard as an element potentially interacting with other hazards. The comprehensive and integrative approach of multi-risk analysis, which considers several hazards and the associated vulnerabilities, best represents situations where several hazards coexist and often interact on the same territory/site. The main advantages of multi-hazard of closed mines are:

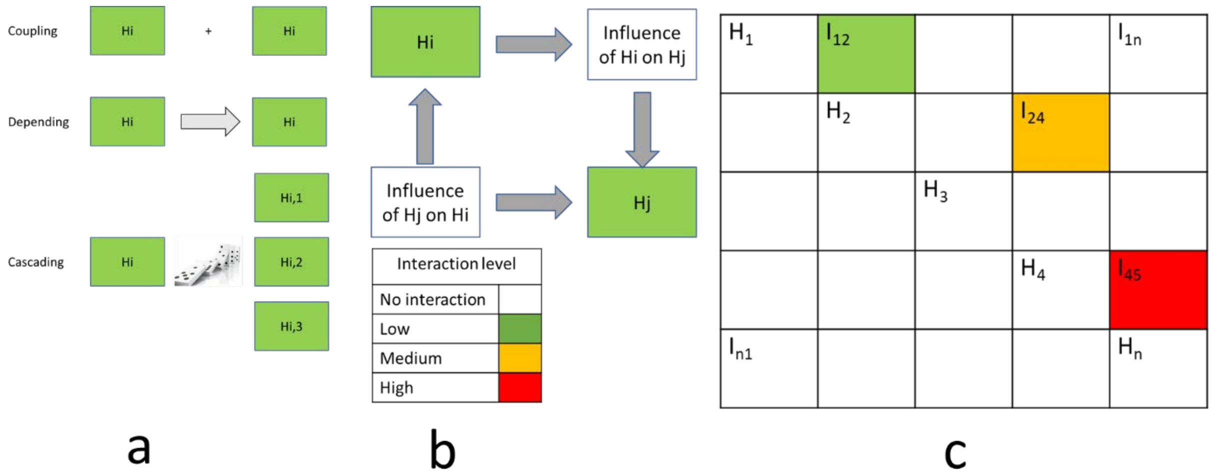
- Improvement of the quality of the risk assessment analysis.
- Identification of the scenarios related to their interactions.
- Better considering the vulnerabilities of a territory exposed to several hazards.
- Improvement of the preservation of the general interests identified around closed mines.
- Improvement in the resilience capacity and sustainability of the territories.

However, multi-hazard risk assessment at local and regional scales remains a significant challenge due to the lack of data, causal factors, and interactions between different types of hazards (Touili, 2018). Multi-risk assessment tools can help decision-makers and provide them with information on mitigation measures (Komendantova et al., 2014).

2.2 Hazard interaction identification and methodology

The assessment of the physical interactions is based on the qualification of the hazard intensity (high level, average level, low level) and the predisposition of each single hazard. We distinguish between three types of interaction: coupling, depending, and cascading. For the coupling interaction, the first hazard amplifies the second hazard. For the depending hazards, only the second hazards can occur if the first hazard occurred. Finally, the cascading interactions occurred when the first hazard triggers several hazards (cascading effect) when several hazards have the same triggering factors and initiating events. In addition, the hazard modifies the conditions of one or more hazards. When one hazard occurs, the conditions for a second hazard may be met, the area becomes vulnerable, or the probability of occurrence becomes higher. The second hazard is entirely or partially related to the first one. A full multi-hazard assessment should consider all the possible hazard sources and identify all possible interaction scenarios, including cascading effects (Garcia-Aristizabal et al., 2015). The interaction between hazards should consider both temporal and spatial scales. The spatial scale refers to the area where the hazard has an impact, and the temporal scale refers to the time scale during which the single hazard acts on the natural environment (Gill and Malamud, 2014).

To assess and presents the hazard interactions, different tools are generally used. Among them: the hazard matrix, fault trees (Eshrati et al., 2015); multi-criteria analysis (Sigtryggsdottir et al., 2015, Merad et al., 2004; Mladineo et al., 2014); the negotiated choice; the implementation of a multi-scale GIS (Global Information Geographic) and statistical modelling of vulnerability including temporal variability (Mancini et al., 2009; Sklodimou et al., 2019) are used to assess the multi-hazards. Additionally, the experts opinion and feedback are generally used to assess the interaction between hazards (Figure 1). The interaction matrix presents the interrelation between n hazards (Hi to Hn), for instance, the source hazard (Hi) can trigger several hazards (H, i to n). Figure 1-a presents the interaction modes between two hazards. Figure 1-b and c, present the construction and mapping of the interaction matrix. The index I_{ij} presents by colure the level of the interaction. The Figure 1-c presents the matrix for five hazards with the green colour means the interaction level is very low and limited, the orange colour means that interaction level is moderate and red colour is very important and has consequences in term of risk assessment.



Hi: the hazard I, it can be considered as the resource hazard, Hj: is the trigger hazard. I1n, the interaction level (green, orange and red) of the hazards HI and Hj.

Figure 1 Different tools for assessing the potential hazards of interaction: a) presents the three modes of interactions, b) and c) present the construction of the matrix of interaction between hazards

3 Multi-hazard assessment in a mining area

3.1 Hazards categories in a mining area

In a mining area, the main hazards likely to occur are grouped into 3 large families for which the assessment methods are different: mining hazards (M), natural hazards (N) and technological hazards (T). Mining hazards are generally gathered into 6 groups: ground movements; combustion and fire in mine deposits and dumps; hydrological and hydrogeological disturbances of mining origin; gas emissions related to mining; endogenous radioactivity of the environment; and environmental pollution, which may impact on water, soil and air.

Natural hazards are related to the environment such as floods, wildfires, etc. (Djizanne et al., 2023).

Technological hazards are related to industrial activities such as industrial pollution, toxic wastes, dam failures, etc. Table 1 summarize of the different hazards can be identified in a closed mining site (Djizanne et al. 2023).

3.2 Mining hazard classification

To assess a single mining hazard two stages are carried out:

- an “information” stage consisting of a description of the mining sites studied (brief history, geographic and geological environment, form and layout of exploitation, inventory of past disturbances) and the collection and evaluation of archive and land data needed to locate and evaluate the hazard. At the end of this stage, one or more informative maps are produced.

- a hazard evaluation stage which defines, for each phenomenon identified as relevant for the sites studied and for each mining configuration, the intensity and predisposition criteria described above and the severity level of the hazard. At the end of this stage, one or more hazard maps are produced based on the number of relevant phenomena and the scope of the territory studied. The hazard study report brings these two stages together. In the mine conditions, three steps are required to qualify the mining hazard: the qualification of the intensity of the hazard and the predisposition. The hazard level is multiplication of hazard intensity by the predisposition factors.

Table 1 Summary of the mining, natural and technological hazards used in this multi-hazard analysis (Djizanne et al. 2023)

Mining hazards (18)	**Code**	**Natural hazards (17)**	**Code**	**Technological hazards (17)**	**Code**
Subsidence	SUB	Subsidence	SUB	Gas explosions	**EXP**
		Sinkhole	SIN	Slick fire (liquid)	**FEN**
Crevasse	CRE	Dissolution	DIS	Flare fire (gas or liquid)	**FET**
Sinkhole	SIN	Clay settlement	SET	Solid fire (solids)	**FES**
Massive mine collapse	MMC	Deep landslide	DLS	Boil over	**BLO**
Settlement	SET	Shallow landslide	SLS	Flammable liquefied gases	**BLV**
Landslide	LS	Erosion	ERO	Liquid product release	**RPL**
		Mudflow	MUF	Gaseous product release	**RPG**
Erosion	ERO	Rocky landslide	RLS	Release of a liquefied gas	**RGL**
Heating	COM	Rock or block fall	RFA	Fire	**IPT**
		Avalanche	AVA	Release of radioactive substances or nuclear radiation	**RSR**
		Earthquake	NSI	Discharge of water bodies	**RME**
Mine gas	GAZ	Forest fire (wildfire)	FFI	Land movement due to human activities	**MVT**
Modification of the groundwater discharge regime	MWR	Settlement, consolidation	SET	Tank burst (Pneumatic energy release)	**EBC**
Modification of the regime of a river	MOR	Lowland flooding	FLO	VCE (Combustion of gases, vapours)	**VCE**
Flooding of topographic low points	TFL	Flooding by runoff and mudslides		Explosive vaporisation of boiling liquid)	**BLV**
Flash flooding - submergence	FFS	Flooding by rising groundwater		An explosion of solids	**ENA**
Induced seismicity	INS				

3.2.1 *Qualifying intensity classes*

The approach developed in France (Salmon et al., 2019) to assess the intensity of a phenomenon consists in identifying the most representative physical parameters in order to characterize the consequences of potentially dangerous events. Thus, one can choose to focus on criteria related to the size of collapse craters, the amplitude of horizontal surface land deformations or the nature, content, and flow of gaseous emissions, etc. Characterizing potential consequences involves referring to the concept of the "severity" of potential events. Severity means the extent of foreseeable consequences to targets that may be present on the surface. This can apply to people (victims), ecological damages and property damages. The number of intensity classes used for analysis may vary based on the context of the study and especially the accuracy and exhaustiveness of the input data. Hazard studies carried out of post-mining risk use the following classes: very low (rarely used, reserved for phenomena with very low occurrences), low, moderate, high and very high (also rarely used, reserved for devastating events of exceptional intensity).

3.2.2 *Qualifying predisposition classes*

Qualification of a predisposition consists of an analysis of the possibility that a phenomenon will appear or manifest on the sub-surface. This analysis is based first on experiential feedback, i.e. on past occurrences of disturbances or nuisances on the site being studied or on a similar site. But a mining site that may not have been the location of known disturbances (some may have been forgotten) may nonetheless feature favourable conditions for a disturbance to occur. Thus, the second approach is to detect these mine configurations by examining the type and configuration of the mining works and their topographical, geological and hydrogeological environment. In addition, because most of the mines in France are very old, it is very rare to have access to all the documents and plans on works, structures and previous mine disorders. Furthermore, some of these documents and plans contain inaccuracies or are based on references that no longer exist. Because of the uncertainties generated by this incomplete and fragmented information, a predisposition analysis may include a criterion for the presumed presence of mining works and/or structures that may point to the presence of a hazard. Thus, this is a complex approach that requires hazard. The predisposition classes are: very unlikely (rarely used), unlikely, likely, very likely.

3.2.3 *Qualifying hazard classes*

Both implicit and explicit approaches are used to combine qualitative values amongst themselves or to cross reference qualitative and quantitative criteria. These may include techniques that use scoring systems, rankings, multi-criteria classification, etc. If the two-way table system is selected, use a matrix like the one illustrated as an example in the table below (Table 2), keeping in mind that each site may require adjustments to fit its specific context. Hazard level is evaluated on a case-by-case basis for each site. The following terminology should be used to qualify the three hazard classes: low, medium, and high.

Table 2 Mining hazard qualification based on the qualification of the predisposition and the intensity qualification

Intensity	**Predisposition**		
	Unlikely	**Likely**	**Highly likely**
Low	🟩	🟩	🟧
Moderate	🟩	🟧	🟥
High	🟧	🟥	🟥

3.3 Mining hazards interactions

The methodology of the multi-hazard assessment is divided into three main steps:

The first step describes the three significant hazards families: mining, natural, and technological. For the considered site, the singles hazards should be identified based on the characteristic of the hazards and the related external factors. For instance: the sinkhole hazard depends on the depth, the dimensions of the underground cavity, the strength of the upper layer. The external factors, for sinkhole hazard, are the flooding, the traffic, the aging, etc.

The second step analysis the potential interaction based on the common factors of the hazards and conditions of the occurrences of the hazards. Possible interactions between hazards are based on the following: their nature (triggering or aggravating), their category (physical or regulatory), and their typology (dependent or independent). The visualisation of the potential interaction is obtained using matrix interaction tool and/or the diagram tool (cf. Figure 1 and Figure 4).

The third step is focused on the identification of the level of interactions between hazards. The level of the interaction is based on the intensity of the single hazards and the level of the interaction.

More concretely, for a mining site, the following questions should be answered by the experts in charge of study to identify the potential interactions between the different hazards:

Interaction conditions: are there specific conditions to be fulfilled? What are these conditions? How to evaluate their likelihood? Or is the interaction systematic?

Intensity: to what extent should a specific source phenomenon modify the target phenomenon intensity? What are the parameters that explain target phenomenon intensity?

Probability of occurrence: which parameters should modify the target probability of occurrence of the phenomenon?

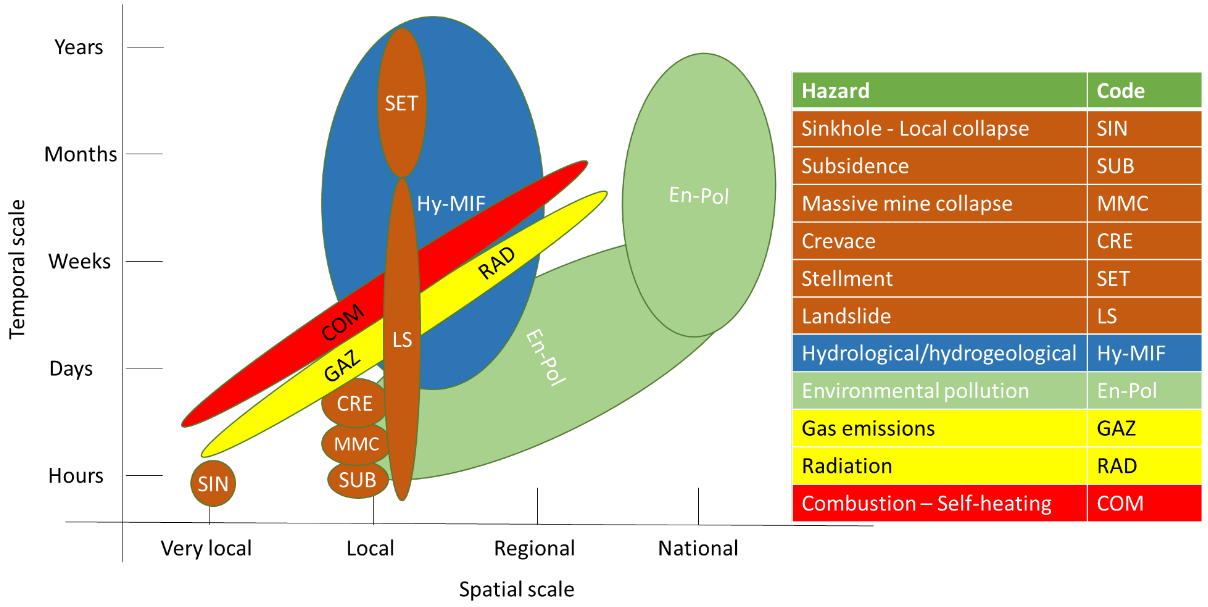
Temporality: will the source and target phenomena coincide, or is there a buffer time between their occurrences? What are the parameters influencing the buffer time?

It Is necessary to carry out a collect of the information related to the mining site. When a lake of data is meted, experts generally can use the information from equivalent sites having the comparable conditions.

Based on the feedback analysis, the following examples of interaction are identified for a mining hazard as a trigger to another mining/natural/technology hazard(s), (Table 3).

The interaction between mining, natural and technology hazards, depends on the scales: spatial scale and temporal scale. Figure 2 represents the potential interaction of several mining-natural hazards using a temporal and spatial scales. The spatial scale covers very limited surface (very local) to large surface (regional land). The temporal scale covers very short event, hours, to very long period (years). Certain mining hazards are very local and very short (e.g.: a sinkhole hazard), the interaction with another hazard may be limited even the interaction theoretically is possible. The interaction should fulfil the following conditions: the occurrence of the H1 corresponds, in time and in space, to the occurrence of the hazard H2. For instance, the flooding of a mining site, large surface, can interact with the sinkhole hazard, if and only if the collapse of the cavity is imminent or shortly can be happened. In this case the level of the interaction between the two hazards can be considered as high.

In the other hand, certain hazard 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).



Hazard	Code
Sinkhole - Local collapse	SIN
Subsidence	SUB
Massive mine collapse	MMC
Crevace	CRE
Stellment	SET
Landslide	LS
Hydrological/hydrogeological	Hy-MIF
Environmental pollution	En-Pol
Gas emissions	GAZ
Radiation	RAD
Combustion – Self-heating	COM

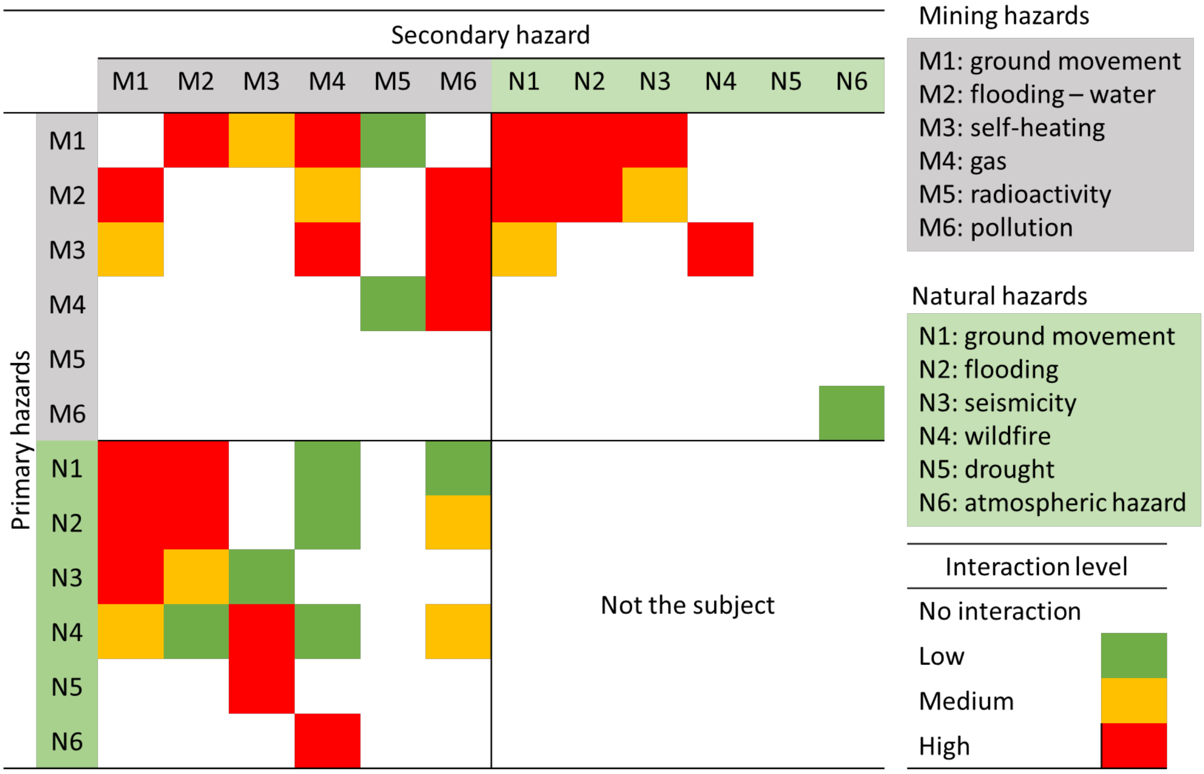
Figure 2 Mining hazard interaction over temporal and spatial scales

An example of interaction matrix of mine hazards (see Table 1) is built for mining and natural hazards, the judgement of the level of the interaction is based on the predisposition factors and the intensity level (Table 4). Three intensity classes are considered (limited, medium and high) and three predisposition classes (likely sensitive, sensitive and very sensitive).

Table 3 Examples of interaction where the primary hazard corresponds to the hazards can trigger with secondary hazards (mining, natural and technology)

Hazard	Primary hazard	Secondary hazards		Ref.
Mining hazard	A collapse of the underground mine (e.g., galleries)	Subsidence	Slope instability, flooding	
	Rising mine gas (Toxic, flammable)	Health and environmental consequences	Fire	
	A massive and uncontrolled inflow of fresh water	Collapse of a salt cavern by dissolution	Subsidence, induced seismicity	43
	Mine flooding	Collapse	Subsidence, slope stability, gas	
Natural hazards	Drought	hydrological and hydrogeological disturbances	Gas flow, ground movement	
	Runoff	surface flooding, increasing water tables	Subsidence, sinkhole, Mine collapse, slope instability, induced seismicity	Chang et al. (2022)
	Wildfire	Pollution	Self-combustion, landslide	
	Earthquake	Landslide, fire, flooding	Self-combustion, landslide, induced seismicity,	(Lenhardt, 2009, Azhari, A.; Ozbay, 2017)
Technology hazards	Dam collapse, sewerage or drinking water networks	Flooding, increasing water tables	Subsidence, sinkhole, Mine collapse, slope instability, induced seismicity	
	Explosion of an industrial site	Wildfire, pollution	Landslide, self-combustion,	

Table 4 Tentative view of interaction matrix of different hazards related to mine closure



Primary hazards	Secondary hazard											
	M1	M2	M3	M4	M5	M6	N1	N2	N3	N4	N5	N6
M1		🟥	🟨	🟥	🟩		🟥	🟥	🟥			
M2	🟥			🟨		🟥	🟥	🟥	🟨			
M3	🟨			🟥		🟥	🟨			🟥		
M4					🟩	🟥						
M5												
M6												🟩
N1	🟥	🟥		🟩		🟩						
N2	🟥	🟥		🟩		🟨						
N3	🟥	🟨	🟩									
N4	🟨	🟩	🟥	🟩		🟨			Not the subject			
N5			🟥									
N6				🟥								

Mining hazards

M1: ground movement
M2: flooding – water
M3: self-heating
M4: gas
M5: radioactivity
M6: pollution

Natural hazards

N1: ground movement
N2: flooding
N3: seismicity
N4: wildfire
N5: drought
N6: atmospheric hazard

Interaction level	
No interaction	
Low	🟩
Medium	🟨
High	🟥

To illustrate the complexity and multiple-interaction possibilities, Figure 3 presents an example of follow organigram where the local collapse hazard (sinkhole- SIN). The figure presents the theoretical potential interaction, each site must be analysed as a unique configuration. The local collapse (sinkhole, SIN) hazard can interact with 9 mining hazards and 6 natural hazards and 2 technological hazards. Furthermore, the sinkhole hazard depends on external factors such as ageing of rockmass (Age), the traffic (Tra) and the overload of backfill material or others (Sur). We can identify 22 potential interaction covering double, simple and cascading interaction. Different scenario should be assessed based on the local site conditions. The seismicity (NSI), flooding (FLO), overload, dam collapse, and others can increase and aggravate the sinkhole hazard level directly or indirectly due to the ageing phenomenon, which decreases the strength of the geomaterial. Thus, assessing the potential interactions requires significant effort to collect the different information. This illustration of the interaction can be built for all the mining hazards listed in Table 1. Based on the classification presented in 2.2, one can noticed two types of interactions: depending and cascading types. For instance: the subsidence depends on the occurrence of the flooding hazard. However, the sinkhole hazard interaction with flooding can be a cascading type because the flooding can trigger the sinkhole hazards. Such analysis can be done for the all hazard interactions.

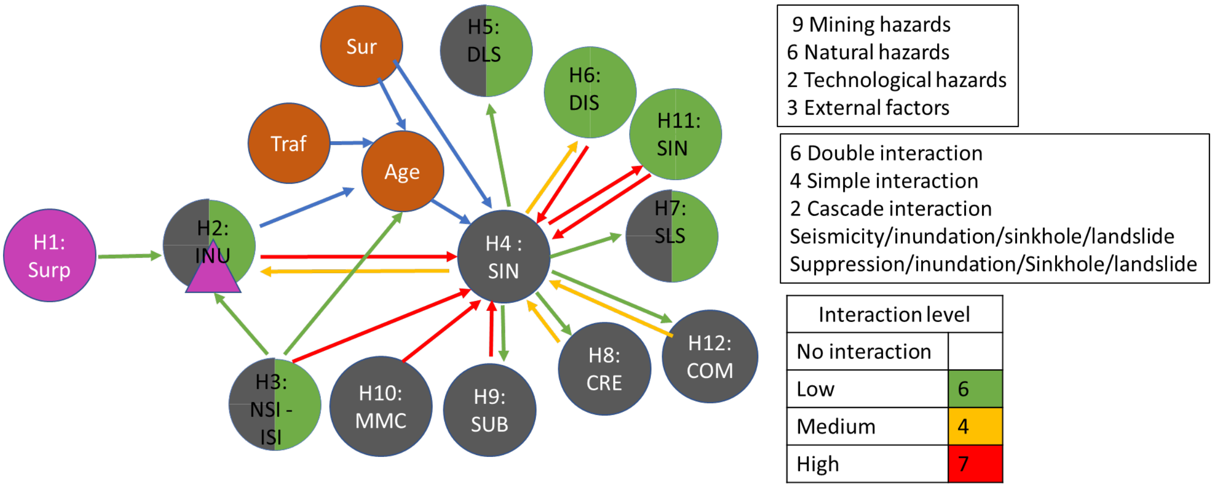


Figure 3 **Examples of mining, natural and technology hazards interaction**

After the identification of the hazard interaction, an adjustment of the level of hazards is mandatory. Line et al. propose to adjust the level of the initial natural hazard based on the level of the interaction. Based on this statement, we adopted the same method for the mining-mining hazard interaction and mining-natural hazard interaction. Table 5 presents the initial hazard level and the adjusted hazard. Three level of interaction are considered (low, medium, and high).

Table 5 **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

4 Application of the methodology to a case study

The methodology presented previously needs to be applied on a real case study. The chosen case study is a closed coal mine in France). Near the surface, above the coal mine, there is an abandoned underground limestone mine. The risk assessment studies were carried out after the shutdown of the mining activities (Al Heib et al., 2023). The 11 mining and natural hazards are presented with their corresponding level in the Table 6.

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

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

The interaction matrix was built (Table 7) based on the assessment of the factor of each hazard (Table 4, Al Heib et al., 2023). This first analysis demonstrated that the flooding hazard (FLO), due to the natural flooding (e.g., heavy rain) can trigger several mining hazards: subsidence (SUB), settlement (SET), landslide (LSG), sinkhole (SIN) and induced seismicity (INS). In addition, the flooding and the water fluctuation can increase the ground movement intensity or level, decrease the strength parameters, and mobilise the faults and discontinuity displacement. The flooding hazard can create a cascading effect. For instance, natural seismicity can trigger flooding and landslide of dumps. One can notice that the flooding (FLO) of the closed coal mine has a high interaction level. In the other hand the wildfire (FFI) has very limited interaction with the flooding (FLO). However, this conclusion should be analysed carefully more precisely based on the single hazard maps to identify the location of the interaction.

Table 7 Multi-hazards interaction matrix and assessment of the level of the interaction: red high, yellow: medium, green: low

Source hazards		**Trigger hazards – mining hazards**						
		Code	SIN	SUB	LSG	SET	COM	INS
Mining	Sinkhole	(SIN)		🟥	🟨	🟥		🟨
	Subsidence	SUB	🟨		🟨	🟥	🟨	🟥
	Landslide	LSG	🟨	🟨		🟨	🟨	🟩
	Settlement	SET	🟩	🟩	🟩		🟩	🟩
	Combustion	COM	🟩	🟨	🟥	🟨		🟩
	Induced-seis	INS	🟨	🟨	🟨	🟨	🟩	
Natural hazards	Sinkhole	SIN	🟥	🟥	🟥	🟥	🟩	🟨
	Settlement (Clay)	SET	🟩	🟩	🟩	🟨	🟩	🟩
	Natural-seis	NSI	🟨	🟨	🟨	🟥	🟥	🟥
	Flooding	FLO	🟥	🟥	🟥	🟥	🟩	🟥
	Wildfire	FFI	🟩	🟩	🟩	🟩	🟥	🟩

In this paper, additional analysis carried out to precise the number and the level of interaction for the 6 mining hazards. We used the interaction matrix, and the flow organigram tools for identify the level of the interaction. We focus the analysis on the mining hazards. For each mining hazard, we calculate the total number of interactions (e.g. 7 for the subsidence). In all, we have identified 55 potential interactions for the six mining hazards (Table 8), a number relatively important of interactions. The Table 8 classes the hazards based on the level of interaction, the first is the sinkhole and the last one (class 5) is the subsidence hazard. The sinkhole mining hazard (SIN) and the induced seismicity (INS) have the maximum number of potential interactions, respectively 11 and 10. However, the high level of interaction (9) concerns the sinkhole hazard (SIN). That means, the sinkhole occurrence can influence and be influenced many natural and mining hazards. The potential interactions of the mining and natural hazards are possible if they coincide in the same place

Table 8 Potential hazard interaction between flooding (natural and mining) and mining and natural hazards. Red arrow: high interaction, low green interaction

Interaction	Interaction type				
Hazard	Low	Moderate	High	Total	Class
SUB	6	0	1	7	5
SIN	0	2	**9**	**11**	1
SET	7	0	3	10	2
LSG	0	4	5	9	3
COM	6	1	1	8	4
ISI	3	4	3	10	2
Total	22	11	22	55	

Based on the total number of interactions for each mining hazard, we classified them, and we suggested the adjustment of the initial level of the 6 mining hazards (Table 6 and Table 9). To adjust the hazard level, we used the high interaction. The following rules are adopted: if the high interaction number is less than 3, no modification of the initial hazard level, between 3 and 6, the initial hazard adjusted by one level (low becomes moderate, moderate become severe). For number of interactions bigger than 6, the initial hazard adjusted by two level (low becomes severe, moderate become severe). For the case study, we noticed that four mining hazards should be adjusted. The sinkhole hazard passes from low and moderate level to severe because of the number of high interactions >6. That means for the zones concerned by the sinkhole, we should be verified the existing of the other mining and natural hazards. For the subsidence, landslide and induced seismicity hazards, the initial level passes from low to medium, and from medium to severe.

Table 9 Initial and adjusted mining hazard level based on the total number of the interaction

Mining hazard	Total	Initial	Adjusted	Initial	Adjusted
SUB	7	Low	Medium	Medium	Severe
SIN	**11**	Low	Severe	Medium	Severe
SET	10	Low	Moderate		
LSG	9	Low	Medium		
COM	8	Low	Low	Medium	Medium
ISI	10			Medium	Medium

5 Conclusion

The work presented in this paper concerns the development and application of a multi-hazard methodology to assess the risk of post-mining areas. The paper begins with a brief presentation of the methodology used in France to assess a single mining hazard. The methodology describing the steps involved in analysing the interaction between natural and mining hazards follows. The matrix of hazard interaction is presented for the interaction between mining-mine hazards, mine-natural hazards, and natural-mine hazards. The interaction organigram tool is used for each primary hazard (mining, natural hazard and technology). This tool completes the matrix of hazard interaction. The methodology focuses also on the scale (spatial, temporal) of the interaction They should be considered for a multi-hazard assessment.

The multi-hazard assessment presents a real advantage for mining regions where this interaction can be significant. However, the stakeholders need to create a group of experts capable to assess the interaction of hazards. The potential consequences of assessing each single hazard separately, should be study for each case study, it can increase the cost of the mitigation of hazards, and in specific cases creating the catastrophic scenario with severe social and economic consequences.

A first real-life case study of a closed coal mine in France was applied. For this case study, 6 mining hazards and 5 natural hazards were identified and assessed. Additional case studies should be used to improve the multi-hazard methodology.

The multi-hazard methodology developed here should also be improved in the frame of the research projects carried out in the mining and post-mining sector. Also, the perspective is to consider the multi-hazard and the multi-risk assessment as the main tool for case studies throughout Europe and elsewhere. Another indicator of success is therefore their adoption as part of wider projects, networks, and dialogues. This methodology must continue to evolve to much higher levels to effectively manage hazards having multiple impacts on past mining land use.

Acknowledgement: This work has received funding from the European Union's Research Fund for Coal and Steel (RFCS) under the European project ‘POMHAZ, https://www.pomhaz-rfcs.eu/’ grant agreement No 101057326 and supported by the Ineris programs.

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