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Post-Mining Multi-Hazard Assessment for Sustainable Development

Mohamed Marwan Al Heib [1,*], Christian Franck [2], Hippolyte Djizanne [2] and Marie Degas [2]

[1] Ineris, Campus ARTEM, 92 Rue du Sergent Blandan, BP 14234, 54042 Nancy, France
[2] Ineris, Parc Technologique ALATA, BP 2, 60550 Verneuil-en-Halatte, France; christian.franck@ineris.fr (C.F.); hippolyte.djizanne@ineris.fr (H.D.)
* Correspondence: marwan.alheib@ineris.fr; Tel.: +33-03-54-40-66-14

Abstract: Today, most mines (coal, iron, and others) in Europe are already closed due to economic, environmental, and societal issues. Therefore, post-mining risk assessment and management remain crucial for mining authorities, policymakers, and planners. In the post-mining period, several hazards are likely to affect the surface areas in the closed mining sites. The impact of closed mines can lead to potentially damaging changes in surface and/or underground water flow, as well as the development of surface instabilities that can affect people or infrastructure, sometimes dangerously. The assessment of the different hazards must consider the interaction between the mining hazards and other risks (natural and technological). Thus, land use planning, particularly the rehabilitation of former mining sites, requires better tools to apprehend the multiplicity of hazards and their constraints. The paper presents a methodology considering the interactions between hazards around closed mines. After recalling the advantages of this multi-hazard analysis, the work consisted of, almost exhaustively, describing the three prominent families of hazards: mining, natural, and technological. Then, the possible interactions between hazards were described according to their nature (trigger or aggravating), their category (technical or regulatory), and their typology (dependent or independent). Finally, an attempt was proposed to evaluate the type and intensity of interactions between hazards. The multi-hazard assessment methodology was applied to a coal mine and showed the complexity and the utility of such a risk assessment analysis to improve risk management in closed mines.

Keywords: closed mines; multi-hazard; matrix; interaction

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1. Introduction

Nowadays, most mines (coal, iron, and others) in Europe are already closed due to economic, environmental, and social issues [1,2]. There are different causes of the decrease in mining activities in Europe; they are related to economic factors, and environmental factors and contexts. The environmental and human impacts of mining activities, mainly coalmines, oblige the European countries to make decisions to close mines. Locals and green campaigners have developed arguments about preserving nature and biodiversity, pointing out that mining can cause serious water and soil pollution and lead to deforestation and biodiversity loss. Additionally, every unprofitable coal mine in the European Union must cease production.

These former mining sites constitute a crucial industrial legacy. Additionally, closed mines are associated with several hazards and risks [3]. Thus, risk assessment and management remain a central objective of the mining industry, mining authorities, and decision-makers. Post-mining management presents a significant concern for the states and regions with a rich mining history. Several European countries must manage large territories where coal mining (open-pit and underground) activities have closed (Czech Republic, Germany, Poland). Other countries are still actively improving risk management even after mine closure (Belgium, France, Spain, and others).

Several hazards are likely to affect surface areas located on former mining sites. Mining hazards can occur sometimes immediately after mining operations cease, but sometimes much later (after several years). Furthermore, the closure of mining sites can lead to job losses following the cessation of mining operations [4].

Impacts from closed mines can result in potentially dangerous changes in surface or/and groundwater flow, and the development of surface instabilities that can sometimes dangerously affect people or critical infrastructure (roads, railways, water distribution). Mine closure can result in hazards, such as geotechnical, induced, or natural seismicity, hydraulic perturbations, flooding events, dangerous or toxic gas emissions, or releases of potentially dangerous chemical substances into the environment [5,6]. The assessment of the different hazards must consider the interaction between mining hazards, i.e., the influence of one hazard on others. Land use planning and specific planning for the adequate rehabilitation of former mining sites require better tools to understand the multiplicity of hazards and their constraints. Managing multi-hazards is a real challenge for communities. Indeed, risk management is a dynamic and iterative process that must address environmental, social, and economic considerations together.

This paper proposes tools to evaluate the interaction between the different mining hazards related to the post-mining era to manage the exposed mining regions. Natural hazards identified in former mining areas also are considered. The matrix interaction approach is described and applied to a coal mining region.

2. State of the Art of Multi-Risk Assessment

2.1. Definitions

The term multi-hazard refers to the existence and the occurrence of several hazards in the same territory. A territory can therefore be subject to several hazards and associated vulnerabilities, but also to possible interactions between hazards. The multi-risk assessment objective is to better manage the interaction between hazards and risks. Hence, it can lead to the identification of suitable mitigation methods based on the multi-hazard and multi-risk assessment results. Delmonaco et al. [7] define multi-hazard analyses 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 [8] 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 or an earthquake, or are merely threatening the same elements at risk without chronological coincidence.

Multi-hazard assessment can be defined as a method or approach that considers more than one hazard in the target area and the interrelationships between these hazards, including their simultaneous or cumulative occurrence and potential interactions [9]. Examples include events that could occur after an earthquake, surface mining activities, or a landslide after heavy rainfall/flooding of a mine pit. In addition, hazards can arise from sustainable conditions with a cumulative nature over time, such as large-scale soil contamination due to the leakage of toxic chemicals that were not detected by the environmental quality monitoring system for many years [10]. Mavrommatis et al. [11] present a comprehensive framework for the 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. Sigtryggsdottir et al. [12] used the interrelation matrix to identify interactions between geohazards that may affect hydropower projects and to optimize the monitoring system.

Multi-risk assessment research started relatively recently, in the 1990s, assessing natural hazards, such as the combination of floods, earthquakes, landslides, volcanic eruptions, snow avalanches, and their potential interactions within a territory [13–17]. Multi-risk assessment was then developed as a decision-support tool for climate change and urban vulnerability [14]. A 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 [18].

In the mining context, closed mining areas are generally affected by several mining and/or natural hazards. In this context, a multi-hazard assessment should be adopted as a risk assessment method. The available data for the different single hazards should be analyzed, i.e., compared, ranked, and aggregated by experts to identify the potential interactions and the levels of the interactions.

2.2. Advantages and Limitations

Separate hazard/risk management increases the cost and decreases the effectiveness of interventions. Additionally, initial feedback from various European countries has shown that separate hazard management decreases the effectiveness of prevention, as it does not consider the effects of interactions between mechanisms and the effects of hazard–risk interactions. It, therefore, appears increasingly necessary to consider risks using a "global" approach, whereas mine managers and local authorities often manage only single hazards. Interest in multi-risk assessment has increased in the last decades at the global and European levels, especially when it comes to applications and initiatives to assess risks from different natural and anthropogenic hazard events [13].

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 their associated vulnerabilities, best represents situations where several hazards coexist and often interact on the same territory/site. 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 [19].

In principle, single-hazard approaches assess 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 consider the interdependencies between the hazards, the assessment presents tools of little relevance to managing complex risks, which is likely to lead to regulatory contradictions. Multi-risk assessment tools can support decision-makers and provide them with information on mitigation measures [15].

2.3. Multi-Hazard Assessment Tools

Liu et al. [20] presented a guideline for the multi-hazard assessment of natural and anthropogenic hazards (see Figure 1). They proposed a three-level framework for multi-risk assessment that considers the possible risk interactions. Liu et al. [20] propose that the first level corresponds to a flow chart that guides the user in deciding whether a multi-hazard and risk approach is required. The second level is a semi-quantitative approach to determine whether a more detailed, quantitative assessment is needed. The third level of the methodology is a detailed quantitative multi-risk analysis based on Bayesian networks. De Ruiter et al. [21] present and discuss several catastrophic events that show the different spatial and temporal ranges at which consecutive disasters can occur, ranging from days to months or even years apart. Furthermore, they mentioned that the risk assessment of a single hazard is not adapted for assessing several regional hazards.

The following risk assessment tools were used: the hazard matrix, fault trees [22]; multi-criteria analysis [23,24]; the negotiated choice; the implementation of a multi-scale GIS (Global Information System); and statistical modelling of vulnerability, including temporal variability [25,26]. The opinions of different experts are generally used to assess the interaction between hazards, mainly in the lack of data and past comparable case studies. The interconnected network of one hazard affecting another also is suggested to define the different hazard interactions [9]. 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). The interaction matrix is not asymmetric. Figure 2 presents an interaction matrix for five hazards. The different levels of hazard interactions can be identified and presented using color codes. The green color means the interaction level is very low and limited, the orange color means that interaction level is moderate, and the red color is very important and has consequences in terms of risk assessment. The fault tree tool helps to identify the interaction between the triggering event (hazard) and the different potential events based on the site conditions and site factors. The fault tree result can help us to understand how systems exposed to multi-hazards can fail.

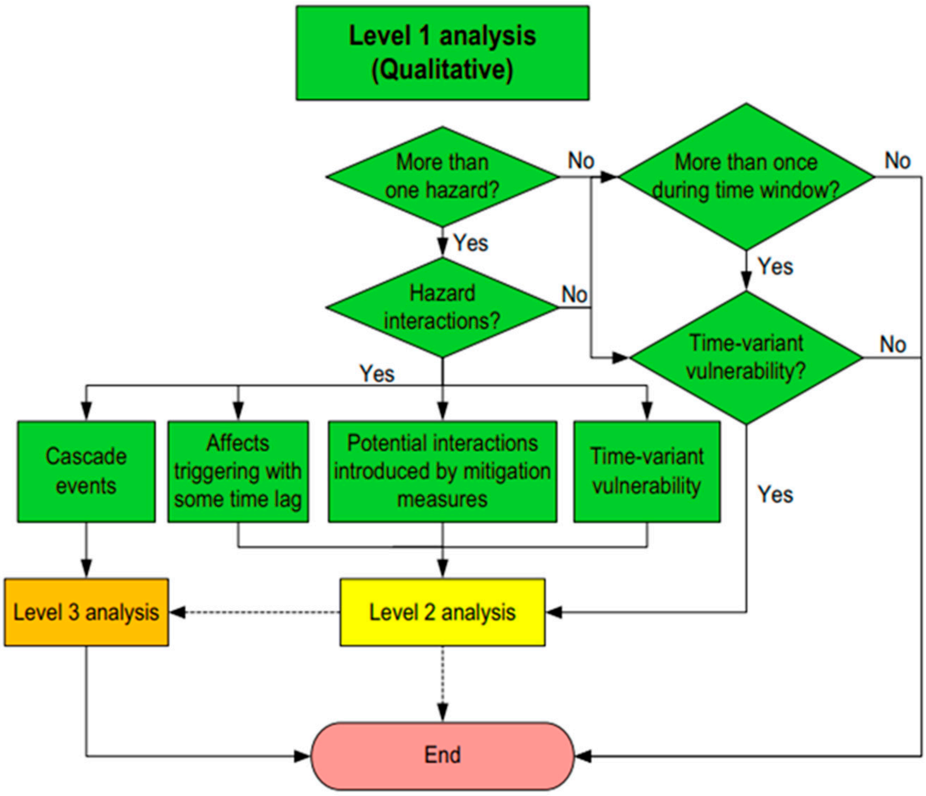


Figure 1. Steps involved in level 1 for the assessment of multi-hazards [20].

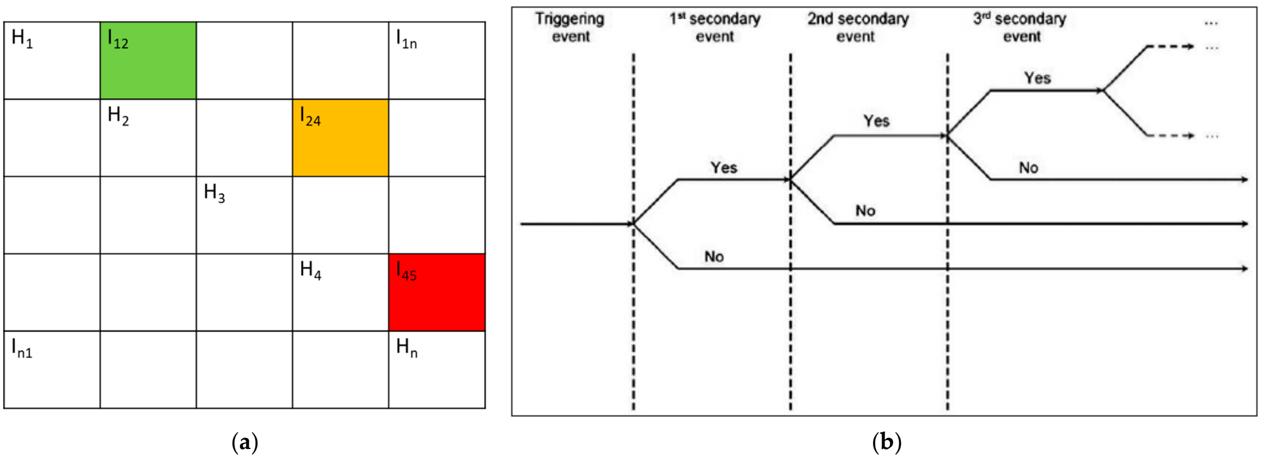


Figure 2. Different tools for assessing the potential hazards of interaction. (**a**) Interaction matrix (H: hazard, i: 1 to n), where color presents the level of the interaction; (**b**) fault tree to evaluate the impact of a triggering hazard (event) on several hazards (events) [22].

A full multi-hazard assessment should consider all the possible hazard sources and identify all possible interaction scenarios, including cascading effects [14]; the cascading effect refers to a hazard which has an impact on several hazards. 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 [27]. They observed that natural hazards influence a range of spatial areas, from fractions of square kilometers to hundreds of millions of square kilometers (a global scale). The timescale of the interaction ranges from seconds to millennia.

2.4. 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) in the study area. In the case where the study area is exposed to multi-hazards, three physical interactions should be verified:

- Coupled or combined dependent hazards. The area has several hazards with the same triggering factors and initiating events. Their consequences are cumulative in the same study area. In this case, one hazard can trigger one or more hazards; there is a direct causal link between one and several hazards occurring consecutively in a territory.
- Sequential dependent hazards (at the same time). 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 is high. The second hazard is entirely or partially dependent on the first.
- Dependent hazards (shifted in time). The occurrence of a first hazard triggers, amplifies, or modifies the second. This is a chain reaction of several hazards. The dependent hazards can lead to a domino or cascade effect. Domino effects extend the diffusion of consequences in space and time beyond the scale of individual hazards.

3. Multi-Hazard Assessment in a Mining Area

3.1. Objectives

In the mining context, the risk and hazard assessment studies have focused on the detailed examination of a single hazard phenomenon [28–32]. 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 [11,23,33–35]. In this context, assessing a single hazard can be unmanageable when multiple hazards must be considered. However, 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 specialized entities and experts need to collaborate.

The objective of this paper is to develop a management methodology to deal with global and multi-hazards related to closed coal mines instead of dealing with each hazard separately. The overall objective is to improve the methodological knowledge for the practical realization of multi-hazard analyses about the main types of post-mining hazards at the scale of a mining basin. The work aims to test and adapt the developed methodology by considering the risks affecting the mining area.

3.2. Hazard Categories in a Mining Area

The main hazards that may occur in target areas marked by the presence of former mining operations are grouped into three prominent families for which the assessment methods are different: mining hazards (M), natural hazards (N), and technological hazards (T). The natural hazards are related to the environment, such as flood, wildfire, etc. The technology hazards are related to industrial activities such as industrial pollution, toxic wastes, dam failures, etc. Table 1 presents a summary of the different hazards that can be identified in a closed mining site [36]. The different hazards can interact with each other and lead to a higher hazard level. In closed mine areas, mining hazards can interact with other mining hazards and with both natural and technological hazards. Possible interactions between hazards are based on the following:

1. Their nature (triggering or aggravating);
2. Their category (physical or regulatory);
3. Their typology (dependent or independent).

Table 1. Summary of the mining, natural and technological hazards used in this multi-hazard analysis [36].

Mining Hazards (18)	Code	Natural Hazards (17)	Code	Technological Hazards (17)	Code
Subsidence	SUB	Subsidence	SUB	Gas explosions	EXP
		Localized collapse (sinkhole)	SIN	Slick fire (liquid)	FEN
Crevasse	CRE	Dissolution (e.g., gypsum, chalk or salt)	DIS	Flare fire (gas or liquid)	FET
Localized collapse (sinking)	SIN	Clay shrinkage or settlement	SET	Solid fire (combustible solids)	FES
Massive mine collapse	MMC	Deep landslide	DLS	Boil over (heavy hydrocarbons)	BLO
Settlement linked to mining works	SET	Shallow landslide	SLS	BLEVE (flammable liquefied gases)	BLV
Deep landslide	DLS	Erosion	ERO	Liquid product release with vaporization of the liquid jet	RPL
Shallow landslide	SLS	Mudflow	MUF	Gaseous product release	RPG
Erosion	ERO	Rocky landslide	RLS	Release of a liquefied gas	RGL
Mudflow	MUF	Rock or block fall	RFA	Fire with the decomposition of toxic products	IPT
Rocky landslide	RLS	Avalanche	AVA	Release of radioactive substances or nuclear radiation	RSR
Rock or block 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, vapors)	VCE
Modification of the regime of a river	MOR	Flooding by runoff and mudslides		BLEVE (explosive vaporization 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				

The advantages of multi-hazard/multi-hazard analysis around closed mines are as follows:

- More careful consideration of the interactions between mining, natural, and technological hazards.
- A better assessment of the intensity of the hazards around closed mines, particularly the scenarios related to their interactions.
- Better consideration of the vulnerabilities of a territory exposed to several hazards.
- A global and integrated view of the risk, which leads to better preservation of the general interests identified around closed mines.
- An improvement in the resilience capacity and sustainability of the territories.

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

- The first step describes the three significant hazard families: mining, natural, and technological. For the considered site, the single 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, and the strength of the upper layer. The external factors for the sinkhole hazard are the flooding, the traffic, the aging, etc.
- The second step treats the potential interaction based on the common factors of the hazards and conditions of the occurrences of the hazards. This step includes the following:
    - Description of the possible interactions, as it is developed and made according to their character (trigger or aggravating), their category (technical or regulatory), and their typology (dependent or independent). The interactions between hazards are based on their nature (triggering or aggravating), their category (physical or regulatory), and their typology (dependent or independent);
    - Visualization of the potential interaction using the matrix interaction tool and/or the diagram tool.
- 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 the 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? Is the interaction systematic?
- Intensity: to what extent should a specific source phenomenon modify the target phenomenon's intensity? What are the parameters that explain target phenomenon intensity?
- Probability of occurrence: which parameters should modify the target probability of the 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?

3.3. Mining Hazards (M)

Various mining hazards can occur in closed mine areas [6,28–31,37–40]. The hazards likely to develop in the case of former mining operations are generally gathered into six 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 water, soil, and air. Table 1 lists hazardous phenomena, the scientific disciplines covered, and their consequences. In total, we listed 18 mining hazards; additional mining hazards can be added depending on the local mining conditions.

Ground movements: different ground movements can occur in the former mine site.

- Localized collapse (sinkhole, SIN): sudden movement due to the presence of exploited areas at shallow depths (<50 m). The localized collapse is manifested by a sudden sinking of several meters in a relatively limited area (dimensions ranging from one meter to a few tens of meters). This phenomenon can also be linked to the presence of old mining shafts.
- Subsidence (SUB): subsidence is a ground movement linked to the presence of large exploitation areas [41], often at greater depths (from a few dozen of meters to several hundred meters). It manifests in the overburden's gradual consolidation and compaction, and the formation of a flexible and continuous subsidence basin. The subsidence is caused by the collapse of old mining operations, especially mines using closed rooms and pillar methods.

- Settlement (SET): settlements are smaller movements linked to the decompaction of materials at low depths (backfilled or collapsed galleries, for example) or to mining deposits (heaps, slurry ponds).
- Landslides (LSG): are generally encountered on deposit structures (slag heaps, slurry ponds) or open cast mines. Slope instability can be manifested by slow or very rapid movements leading to the displacement of materials. Shallow landslides involve the movement of a small amount of material (gullying, for example), whereas deep landslides involve the most significant volumes. Movements of open-cast mining faces may occur during, or a long time after, the work has stopped; gullying is linked to runoff, landslides, boulder falls, and mass collapses. Different kinds of mass movements can be considered in mining hazard analysis, i.e., mudflows hazard (MUF), erosion (ERO), and rockfalls (RFA).

Combustion and fire in mine deposits and dumps (COM): this hazard is mainly linked to the heating of land on mine dumps, coal, and lignite mines. The heating is a phenomenon linked to the combustion of coal residues contained in certain waste rock deposits. Very high temperatures (several hundred degrees) can be reached. Combustion hazards can trigger other hazards; for example, the heating of the coal veins can lead to land collapses and surface subsidence.

Water hazard hydrological and hydrogeological disturbances/Flooding (FLO): the mine closure is accompanied by a rise in the water table, which gradually returns to its natural level, partially or completely filling the reservoirs and voids created by mining, and joining the surface hydrographic network or the topographical depressions which the mining may have created. These hydrological and hydrogeological disturbances may be detrimental to land or subsoil use. Associated mining hazards include the modification of emergencies, flooding of topographic low points or particular points of the basin, modification of a watercourse regime, and severe floods such as the failure of the bottom surface structures.

Gas hazards (GAZ): the extraction of underground mines contributed to creating a reservoir that can fill with gas being released from the exploited rock or further away. This gas is a mixture of multiple components with varying contents. Mine gas may be directed toward the surface through natural drains (faults, fractures, cracks, and others) or artificial drains (shafts, galleries, and others) through various mechanisms. Mining may have also generated new drains (cracks, crevices) that link underground gas-emitting formations with the surface. These gas emissions are potentially dangerous. Furthermore, the natural gases in the surrounding rock mass can sometimes move more freely due to the destruction caused by mining. High emissions of the radioactive gas radon are sometimes observed, concerning the nature of the rock mass surrounding the mine.

Pollution of water, air and soil (POL): water seeps into flooded mining lands and is loaded with various chemical compounds. They can potentially pollute groundwater and water sources. One of the causes of post-mining pollution and nuisance is the interaction between mining operations and water flows, which can lead to soil, surface water, and groundwater contamination. Surface conditions (air, precipitation) can influence the discharge of substances into the environment, which is potentially harmful or dangerous to people and ecosystems.

3.4. Natural Hazards (N)

Natural hazards harm humans and are caused by extraneous forces [27]. They have been mapped at all territorial scales. At the scale of the territory, such as around closed mines, natural hazards evolve due to anthropogenic factors and the impact of climate change. The natural phenomena can be described based on the occurrence and impact. Table 1 summarizes the main natural hazards that can be identified in closed mine sites [36].

Ground movements refer to any more or less brutal movement of the soil, 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, and others) or anthropogenic stresses (earthworks, vibration, deforestation, mining and quarrying, and others). Ground movements can be grouped into five categories:

- The collapse of natural caverns or shallow anthropogenic undergrounds;
- Landslide, corresponding to the mobilization and propagation of rock masses, from rock and boulder falls to mass landslides (up to several million m3);
- Landslides correspond to the movement of loose or rocky terrain along a fracture surface mainly due to high water saturation of the soil, and they also include mudslides;
- Progress of a coastal dune front inland;
- Differential settlements or shrinkage and clay swelling.

The seismicity hazard is associated with potential earthquakes in an area, and wildfire hazard refers to a large and destructive fire that spreads quickly through woodlands or bush.

A flooding hazard includes several types of flooding (lowland flooding, torrential flooding, marine submersion, rising groundwater, and others). The drought and shrinkage/swelling of clay soils can be linked. The drought hazard can also be linked to hydrological and hydrogeological disturbance. Atmospheric hazards include a variety of wind-related hazards: cyclones and hurricanes, storms and squalls, waterspouts, lightning, hail, snow, freezing rain, and forest fires.

3.5. Technological Hazards (T)

A technological hazard [8,36] is a hazard arising from technological or industrial conditions, including accidents, dangerous procedures, infrastructure failures, or specific human activities, that may cause a loss of life, injury, illness or other health effects, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage. Technological hazards may include industrial pollution, nuclear radiation, toxic wastes, dam failures, transportation accidents, factory explosions, fires, and chemical spills. Technological hazards also may arise directly from the impacts of a natural hazard or other incident or event.

3.6. Mining Hazards Interactions

In a former, now closed, mining area, several mining hazards can be identified and may potentially interact [41–44]. Based on the methodology described in 2.4 and the expert opinions, the interactions between mining hazards and natural hazards are identified. The three steps (identification of a single hazards, identification of the potential interaction, and the finally the assessment of the level and type of the interaction) should be followed. In mining sector contexts, the following configurations can be identified: A triggering mining hazard is a mining hazard which triggers another mining hazard, a natural hazard, or a technological hazard. An aggravating mining hazard or sequential dependent hazard is a mining hazard that increases instantaneously or in a delayed manner, such as a natural or technological hazard.

The following real examples highlight the interaction between mining and natural hazards. For instance, the Aberfan disaster (1966), is an excellent example of the interaction between the heavy rain (natural hazard) that triggered the slope instability of coalmine spoil (mining hazard). The landslide of the spoil happened after three weeks of heavy rain; consequentially, the tip was saturated, and spoil became completely unstable. The consequence of this disaster was that 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 of tailing dams have been recorded since the beginning of the 20th century [45]. The analysis was carried out for failures before 2008, and nearly half of the cases are linked to exceptional climatic events, as was the case in 1936 in Sardinia where a strong flood partially destroyed an old tailings dam [45]. Azam and Li [46] highlight that the failures of tailing dams due to exceptional rains have increased from 25% to 40% since 2000. Lecomte et al. [47] mentioned the case of a shaft (coal mine) located at Tirphil, New Tredegar (England). The collapse of the shaft was reported in November 2010. Due to water ingress from the culvert, the collapse grew, and the following morning it was approximately 10 m in diameter, 15 m deep, and filled with water to approximately 4 m from road level. The shaft is connected to the water drainage of the site and that was considered as the main cause of the shaft collapse.

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

- A collapse of the underground mine (e.g., galleries) induces subsidence on the surface, which can cause a modification of the slopes of the water anthropic networks and, therefore, frequent flooding;
- A rising mine gas can be flammable or toxic and can cause health and environmental consequences;
- A massive and uncontrolled inflow of fresh water in salt mines or brine into the mines operated by the room and pillar can induce the collapse of a salt cavern created by dissolution, which can consequently cause ground movement [41];
- A mine flooding can trigger or worsen the sinkhole-type terrain movement hazard. For example, an upwelling of underground water contributes to the flooding of mining voids which can cause land uplifts or lead to surface flooding, sloughing, or progressive subsidence.

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

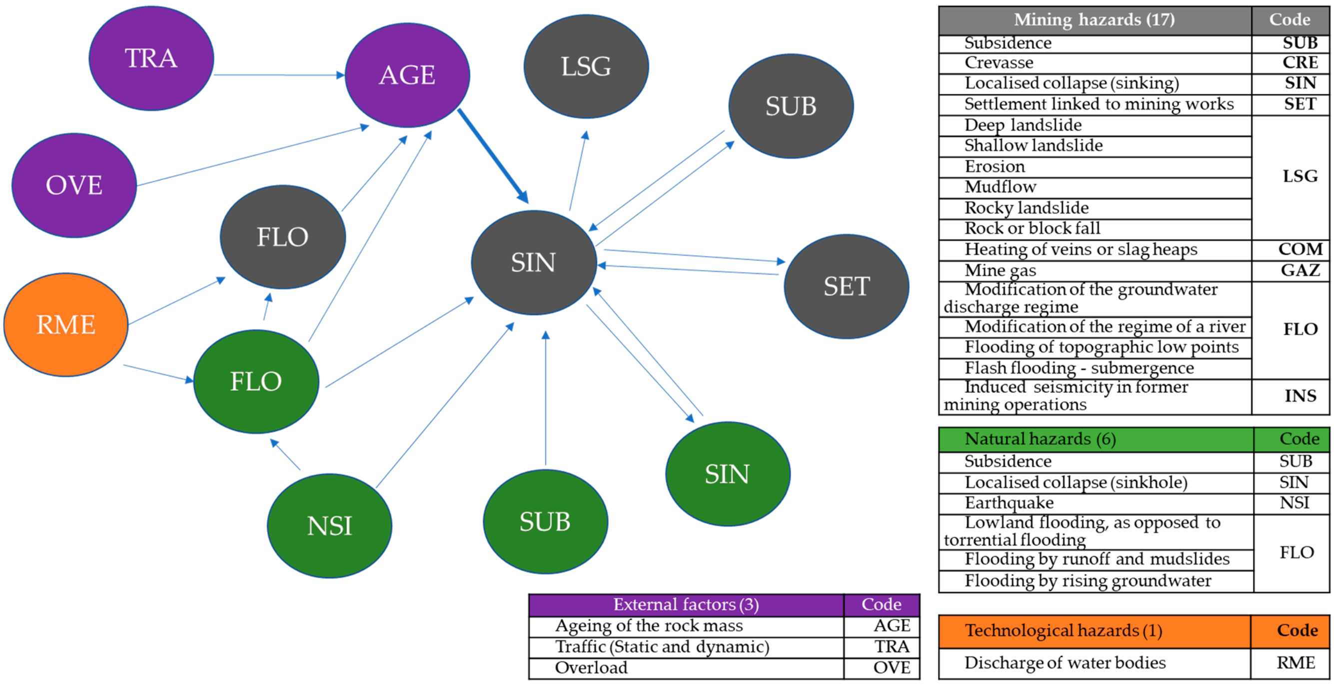
- A drought hazard may be related to hydrological and hydrogeological disturbances in mining reservoirs, and thus modifies the gas flow to the surface. Additionally, intensive or inadequate use of available water may influence groundwater levels, which consequently causes ground movements on the surface in closed mines. The decline in mining water reservoirs causes the swelling, and the shrinkage of clay soils may also be linked;
- 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 rains can cause mine collapses, especially for works located at shallow depths;
- Surface flooding is likely to cause ground movements, particularly subsidence, the settlement of mining lands, or even mining collapses;
- Long-lasting rains and violent thunderstorms can be the origin of a significant flood or a slow rise in the water tables, which can cause river overflows, which are spread by the runoff hazard in urbanized areas;
- Wildfires in closed wooded open-cast mines: these fires cause land movements, falling blocks, and mud flows (sudden soil erosion in the event of precipitation and others);
- Earthquakes, cyclones, or torrential downpours can destabilize the slopes, which in turn cause landslides (mines and slag heaps). Earthquakes can, but much more rarely, cause the collapse of shallow mines operated by abandoned rooms and pillars [33,35]. The slope instability of an open-pit mine can be triggered by an earthquake where the focal distance is at a distance equal to or less than 100 km and a magnitude greater than 6.0 [35].

The following cases of interaction identified the technological hazard as a trigger hazard and the mining hazard as an aggravating hazard. Herein are some examples of where specific technological hazards can interact with the mining hazards:

- The failure of specific structures such as dams and sewerage or drinking water networks can directly trigger the flooding of closed mines and cause widespread or localized collapses;
- The rupture of exceptional bridges/works can cause surface movements of land on the flanks/fronts of open-sky mines and cause underground disorders;

- Intensive agriculture, such as large cereal farms, causes soil erosion, which can lead to the mechanical instability of the soil, such as flow, and a landslide of underground mining works;
- An explosion of an industrial site can cause ground movements and pollute the soil and groundwater;
- Boreholes can bring water into contact with the anhydrite layer, causing ground movements (swelling of the anhydrite) and then transforming into gypsum;
- Urbanization as a technological hazard can cause localized collapse hazards.

To illustrate the complexity and multiple interaction possibilities, Figure 3 presents the local collapse hazard (sinkhole, SIN) interaction with mining hazards, natural hazards, and technology hazards. The local collapse (sinkhole, SIN) hazard can interact with four mining hazards (subsidence, SUB; settlement SET; landslide, LSG), four natural hazards (subsidence, SUB; sinkhole, SIN; natural seismicity, NSI; flooding, FLO), and one technological hazard (flooding, discharge of water bodies, RME). The sinkhole depends on external factors such as the ageing of rock mass (AGE), the traffic (TRA), and the overload of backfill material or others (OVE). The seismicity (NSI), flooding (FLO), overload, dam collapse, and other hazards 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 in order to collect the different information. This illustration of the interaction can be built for all the mining hazards listed in Table 1.



Mining hazards (17)	Code
Subsidence	SUB
Crevasse	CRE
Localised collapse (sinking)	SIN
Settlement linked to mining works	SET
Deep landslide	LSG
Shallow landslide	
Erosion	
Mudflow	
Rocky landslide	
Rock or block fall	
Heating of veins or slag heaps	COM
Mine gas	GAZ
Modification of the groundwater discharge regime	FLO
Modification of the regime of a river	
Flooding of topographic low points	
Flash flooding - submergence	
Induced seismicity in former mining operations	INS

Natural hazards (6)	Code
Subsidence	SUB
Localised collapse (sinkhole)	SIN
Earthquake	NSI
Lowland flooding, as opposed to torrential flooding	FLO
Flooding by runoff and mudslides	
Flooding by rising groundwater	

External factors (3)	Code
Ageing of the rock mass	AGE
Traffic (Static and dynamic)	TRA
Overload	OVE

Technological hazards (1)	Code
Discharge of water bodies	RME

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

3.7. Multi-Hazard Matrix Interaction of Mine Hazards

An example of the interaction matrix of mine hazards (see Table 1) is built, and the judgement of the level of the interaction is based on the predisposition factors and the intensity level. Experts worked together to suggest interaction levels between mining hazards. The mining hazard is qualified according to its intensity and the predisposition of the site studied [44]. Three intensity classes are considered (limited, moderate, and high) and three predisposition classes (not very sensitive, sensitive, and very sensitive). They allow the hazards to be assessed by prioritizing the damage or potential nuisances according to the nature of the phenomena, or by analyzing the possibility of the appearance or manifestation on the surface of a phenomenon. The interaction level between hazards is estimated from the factors determining their intensity on the one hand, and their probability of occurrence on the other. 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 were hierarchized into three levels compared to a method described in the methodological guide for developing mining risk prevention plans: high, medium/moderate, and low. Figure 4 shows a tentative view of interactions that phenomena in the first column (source phenomenon) may have on phenomena in the first row (target phenomenon). Thanks to the interaction matrix, one can identify the role and the interaction between the flooding hazard (FLO) and the other mining hazards. The interaction between the flooding hazard (FLO) and the sinkhole hazard (SIN) is high level.

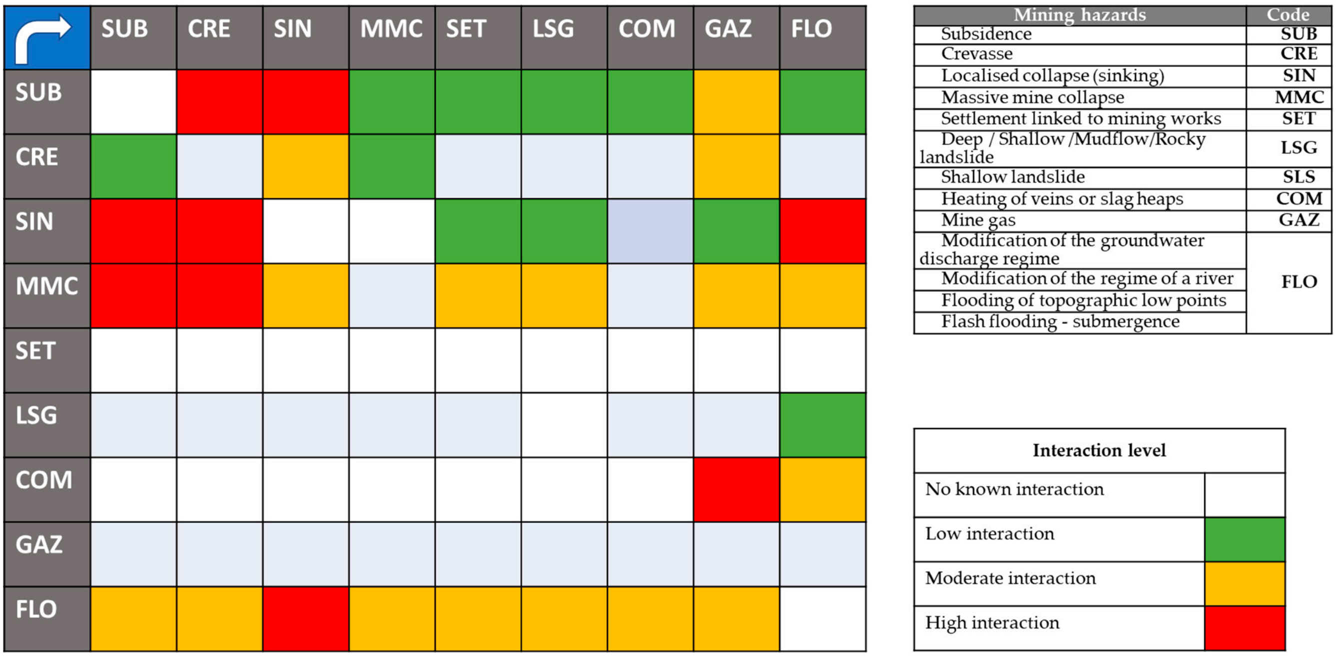


Figure 4. Tentative view of interaction matrix of different hazards related to mine closure.

4. Application of the Methodology to a Case Study

The case study concerns a closed coal mine (France). Near the surface, in addition to the mine, there is an underground limestone mine. The risk assessment studies carried out after the shutdown of the mining activities identified several hazards; they can be grouped as follows:

- Mining hazards (6): ground movements (subsidence, sinkhole, and landslide), self-heating, and induced seismicity;
- Natural hazards: ground movements (sinkhole, settlement), wildfire, flooding, natural seismicity;
- Technological hazards: transport of dangerous goods.

Table 2 presents the different identified hazards (mining and natural hazards) and their intensity level. The mining hazards (6) are mainly low to medium level, while the natural hazards (5) are classified as medium to very severe.

The interaction matrix was built based on the assessment of the factor of each hazard (Table 3). Based on the collected information, three types of physical interaction were identified: between two or no more natural hazards, between two hazards or more natural and "natural or man-made cavities outside mines" hazards, and between two hazards or more natural and underground or open-pit hazards. For each interaction, the following observations can be summarized.

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

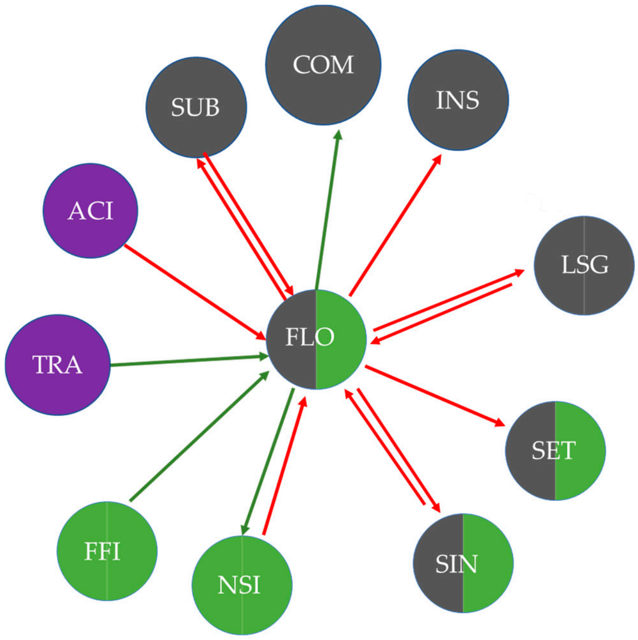
Hazard		Low	Medium	Severe
Mine hazards (6)	Sinkhole (SIN)			
	Subsidence (SUB)			
	Landslide (LSG)			
	Settlement (SET)			
	Combustion (COM)			
	Induced seismicity (INS)			
Natural hazards (5)	Sinkhole (SIN)			
	Clay shrinkage—swelling (SET)			
	Natural seismicity (NSI)			
	Flooding (FLO)			
	Wildfire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

Table 3. Multi-hazards interaction matrix and assessment of the level of the interaction: red: high, yellow: medium, green: low.

Source Hazards		**Trigger Hazards—Mining Hazards**					
		Sinkhole (SIN)	**Subsidence (SUB)**	**Landslide (LSG)**	**Settlement (SET)**	**Combustion (COM)**	**Induced Seismicity (INS)**
Mining hazards	Sinkhole (SIN)						
	Subsidence (SUB)						
	Landslide (LSG)						
	Settlement (SET)						
	Combustion (COM)						
	Induced seismicity (INS)						
Mining hazards	Sinkhole (SIN)						
	Clay shrinkage—swelling (SET)						
	Natural seismicity (NSI)						
	Flooding (FLO)						
	Wildfire (FFI)						

The flooding hazard (FLO), due to the natural flooding (e.g., heavy rain), can trigger several mining hazards: subsidence (SUB), settlement (SET), landslide (LSG), and sinkhole (SIN). The flooding and the water fluctuation can increase the ground movement intensity or level, decrease the strength parameters, and mobilize the faults and discontinuity displacement. Both the natural seismicity (NSI) and the flooding hazard (FLO) can increase the ground movement (SIN, SUB, and LSG) hazard occurrence and level in the mining area. Natural seismicity (NSI) and flooding (FLO) hazards can coincide in the same area where shallow cavities (limestone mines) and coalmines exist, and they are characterized by a high to medium level of a ground movement hazard (sinkhole). In this case study, the multi-hazard analysis increases the initial level of mining hazards. Furthermore, the occurrences of the natural hazards (flooding, natural seismicity, and collapse of the limestone mines) and the mining hazards (flooding and the collapse of the coal mine galleries, subsidence) correspond to a cascade scenario. The likelihood of a cascade scenario is relatively low, but it is undoubtedly zero.

Figure 5 presents the potential interactions where eight hazards can interact if they coincide in the same place. The flooding hazard can create a cascading effect. For instance, natural seismicity can trigger the flooding and landslide of dumps. One can notice that the flooding (FLO) of the closed coal mine has a high interaction level. On the other hand, the wildfire (FFI) has very limited interaction with the flooding (FLO). However, this conclusion should be analyzed carefully based on the single hazard maps to identify the location of the interaction.



Mining hazards (15)	Code
Subsidence	SUB
Localised collapse (sinking)	SIN
Settlement linked to mining works	SET
Deep landslide	LSG
Shallow landslide	
Erosion	
Mudflow	
Rocky landslide	
Rock or block fall	
Heating of veins or slag heaps	COM
Modification of the groundwater discharge regime	FLO
Modification of the regime of a river	
Flooding of topographic low points	
Flash flooding - submergence	
Induced seismicity in former mining operations	INS

Natural hazards (5)	Code
Localised collapse (sinkhole)	SIN
Earthquake	NSI
Wildfire	FFI
Lowland flooding, as opposed to torrential flooding	FLO
Flooding by runoff and mudslides	
Flooding by rising groundwater	

External factors (2)	Code
Accident	ACI
Traffic (Static and dynamic)	TRA

Interaction level	
No known interaction	
Low interaction	
Moderate interaction	
High interaction	

Mining hazard
Natural hazard
Mining and Natural hazard

Figure 5. Potential hazard interaction between flooding (natural and mining) and mining and natural hazards. Red arrow: high interaction, green arrow: low interaction.

5. Conclusions

Post-mine activities can present different potential hazards. The work presented in this paper is devoted to the analysis of the natural and man-made hazards to develop a comprehensive methodology for assessing the risk in post-mining areas. The paper presents the analysis of multi-hazard interactions and their assessment in closed mines to review the consideration of physical interactions between various hazards. The paper presents first the different natural, mining, and technology hazards that can be identified in a mining site. Then, it proposes a methodology considering the interactions between hazards around closed mines. After recalling the advantages of this multi-hazard analysis, the work consisted, on the one hand, of describing in an almost exhaustive manner the three prominent families of hazards: mining, natural, and technological. Then, the possible interactions between hazards were described according to their character (trigger or aggravating), their category (technical or regulatory), and their typology (dependent or independent). Finally, an attempt to assess the type and intensity of interactions between hazards has been proposed. This assessment focuses on analyzing possible interactions between hazards (mining, natural, and technological), possible combinations of several hazards, or the chain or domino effects. Two tools were presented: the matrix of interaction and the interaction diagram. The two tools are complementary. The results highlight the importance of considering the hazard interactions based on the analysis of each single hazard and the feedback from experts and real case studies. The multi-hazard assessment methodology was applied to coalmines and showed the complexity and the utility of carrying out such a risk assessment analysis, improving the risk management in closed mine areas where other hazards can occur.

The multi-hazard assessment presents a real advantage for mining regions. However, the policymakers and stakeholders should construct a panel of experts capable of assessing the interactions between the hazards. The potential consequences of assessing each single hazard separately can increase the cost of the mitigation of hazards, and, in specific cases, can create the catastrophic scenario with severe social and economic consequences.

The multi-hazard methodology developed here for post-mining sites, and the knowledge generated, should be improved in the frame of the research projects conducted in the mine and post-mine sectors. In addition, the perspective is to consider the multi-hazard and multi-risk assessment as the main tool for case studies throughout Europe and elsewhere. Another indicator of success is therefore their uptake within wider projects, networks, and dialogues. Of course, this methodology practice must continue to evolve.

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