Post-Mining Multi-Hazards evaluation for land-planning

PoMHaz

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

D7- Deliverable D2.2: Critical analysis and methodology of multi-hazard interaction

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

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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 (France).
GEODERIS	French mining expert
NGO	non-governmental organization
MLC	Mining life cycle
PPRM	Plan de Prevention de risques miniers
RFCS	Research Fund for Coal and Steel
UAV	Unmanned Aerial Vehicle.

1 Executive Summary

This Deliverable is part of the POMHAZ project, **Post-Mining Multi-Hazards evaluation for land-planning.**
The main objective of POMHAZ is to identify the interaction between the post-mining hazards for coalmines in Europe and to develop tools for facilitate the management of the post-mining hazards in coal region.

The deliverable addresses 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 implications.

The main objective of the deliverable is to summarize 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 document is divided into 8 chapiters. The first chapiter corresponds to an introduction and background of the mines and post-mining in Europe. The second chapiter deals with the hazard assessment and the multi-hazard assessment. Then a chapiter is dedicated to multi-hazard analysis in the context of the post-mining areas. The chapiter 7 presents the European experience for evaluating a single hazard. A comparison and a critical analysis of the different approaches are carried out. The partners collected the information about the main post-mining hazards identified in their country and they discussed the existing methodology and tools used for assessing the single post-mining hazards.

The main outcome of this analysis is showing that the number of the post-mining hazards considered varies from one country to another. The main post-mining hazards related to abandoned coal-mines in Europe are: ground movement, pollution, hydrological disturbance. But also, in Poland, the induced seismicity and radiation are considered as post-mining hazards related to coalmine.

The partners presented examples illustrating the national assessment of one single post-mining hazard. The examples are showing several common steps, such as the mine description, the evaluation of certain factors related to mining method of the but also slight differences regarding the class of intensity, the probability of occurrence. Additionally, we noticed that no one assess to assess the post-mining hazards.
For instance, in Greece, the monitoring is the main tool used to assess the potential of the occurrence of hazards. Within each country, the monitoring is mainly used after the mitigation of the post-mining-hazards.
The document highlights the main advantages of the multi-hazard approach in post-mining areas relatively to the analysis used for assessing a single hazard. The multi-hazard assessment of post-mining hazards is not common. The interaction matrix, the organigram of hazard interaction and interaction index are presented, and they can be used for evaluating the potential interaction between hazards and the level of interactions.

At this stage, there are no real approaches or methodologies for assessing the hazards interaction in the different European countries. However, we noticed the correlation between

hazards is generally considered. In Germany, they start to integrate them in the general risk assessment in the post-mining sites.
The European directives, mainly for water and pollutions, are very useful and certain countries using the European directives for assessing the post-mining hazards.
Additionally, the social-economic impact of the occurrence of several post-mining hazards, multi-hazard occurrence, is not considered.
In conclusion, the critical analysis clearly highlighted the lack of multi-hazard analysis. Different tools used for multi-hazard analysis of natural hazards can be used in the context of the post-mining hazards, such as multi-hazard matrix, interaction organigram etc. The multi-hazard assessment will present important benefits for stakeholders.

The next steps are the studying of the multi-hazards and multi-risks, methods and regulations for the identification, analysis, classification and assessment of post-mining hazards for their respective countries, and with particular reference to their areas of specific expertise.

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 closure of the mines. 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 2.3. Development of a methodology for post-mining hazards interactions identification.

This deliverable concerns the Task 2.2.

2.2 Description of the T2.2

As task leader, Ineris has provided involved partners with a template in order to collect information about existing tools for studying the multi-hazards and multi-risks in general, methods and regulations for the identification, analysis, classification and assessment of post-mining hazards for their respective countries, and with particular reference to their areas of specific expertise.

GIG has been responsible for critical analyses of data gathered in the areas of towns involved in the project and data from SRK in Polish coalmines. CERTH and PPC will carry out a general assessment for the Greek open pit lignite mines, focusing mostly, but not exclusively, on geotechnical issues. DMT-THGA will collate data on different monitoring techniques relative to mining hazards and distinguish in terrestrial methods (from visual inspection, sensors etc.) remote technologies like UAV and satellite data with regard to their application on the different hazards and their interactions. This analysis will include the technical requirements, the conditions of applicability, the strengths and weaknesses of each technology, cost and benefits, etc.

TU BAF will investigate existing European and major global standards and guidelines for managing risks related to abandoned mining sites, e.g. recommendations of the German Association of Geotechnics and extract best practices.

With the support of other partners of the Task, Ineris will likewise review tools and gaps in existing methods in relation to their ability and gaps to integrate the concerned multidimensional and heterogenous hazards into decision-making, including the socio-economic dimension. All involved partners will contribute to the performance of a literature review on existing methods for post-mining hazards assessment. Ineris will carry out a synthesis of collected information that will have two objectives:

- To share information about existing tools across Europe to assess and integrate in a single and consistent framework several specific hazards / hazards interactions and their socio-economic implications;
- To identify gaps in terms of methods for evaluating specific hazards / hazards interactions, and their socio-economic implications.

The deliverable related to this task is D2.2 (D7) is the Critical analysis and methodology of multi-hazards interactions with contribution of the Ineris (responsible of the deliverable), CERTH, GIG, DMT-THGA and PPC.

The present document is the main deliverable of the task, summarizing the feedback and the critical analysis regarding the risk assessment for multi-hazards in the mining sector and, more precisely, in post-mining areas. This task delivers outputs to Task 3.1 (Development of the post-mining risks assessment).

In the following chapter, the work done for this task of the project is in line with the DoA of the project. It is carried out by all partners of the project. GIG and SRK, DMT-THGA and TUB, PPC and CERTH shared their methodologies and the practices in the different European countries.

3 Multi-hazard assessment

3.1 Definitions

The Risk is communally calculated as:

Risk = Hazard x Vulnerability x Consequence x Correlation Factor

Where:
Vulnerability is the probability that the given facility will fail when subjected to the given hazard intensity.
Consequence is a measure of loss in terms of dollars, loss of life, or other comparable parameters.
Correlation Factor is a measure of the likelihood that the hazard will impact multiple facilities in a single event.

"Hazard" is a commonly used term in risk prevention. It means the probability that a phenomenon 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, structures, infrastructures and goods.
In this context, the concept of probability of occurrence refers to how sensitive a site is to being affected by a phenomenon.
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In this context, the concept of probability of occurrence refers to how sensitive a site is to being affected by a phenomenon. Regardless of what type of mining-induced event is anticipated, the complexity of mechanisms, the heterogeneous nature of the natural surroundings, the incompleteness of the available information and the fact that numerous disturbances, aftereffects or nuisances are not repetitive all demonstrate that it is generally impossible to reason in terms of a probabilistic quantitative approach. Therefore, we use 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.

3.2 Single hazard assessment

The Task 2.1 objective is the information collect of the main mining hazards can occur. The qualification of each hazard should be carried out.
When analysing the risk management/assessment issues in the mining sector, different hazards can occur at various stages of the mining life cycle (MLC). MLC includes six phases:

- exploration and feasibility,
- design and planning,
- construction and installation,
- exploitation and mineral processing,
- mine closure,
- and post-mining land use (Tubis et al., 2020).

The post-mining risk assessment assesses the risks and opportunities associated specifically with closure and post-closure. The risk assessment of coal mine hazards follows the principle given steps presented in Figure 1 and it is divided into three main steps:

- the collection of data relating to the industrial history of the site.
- the identification and the assessment of the hazards (predisposition, intensity, and level) and the risk (hazard crossed with the vulnerability).
- the risk management including prevention, mitigation, and monitoring.

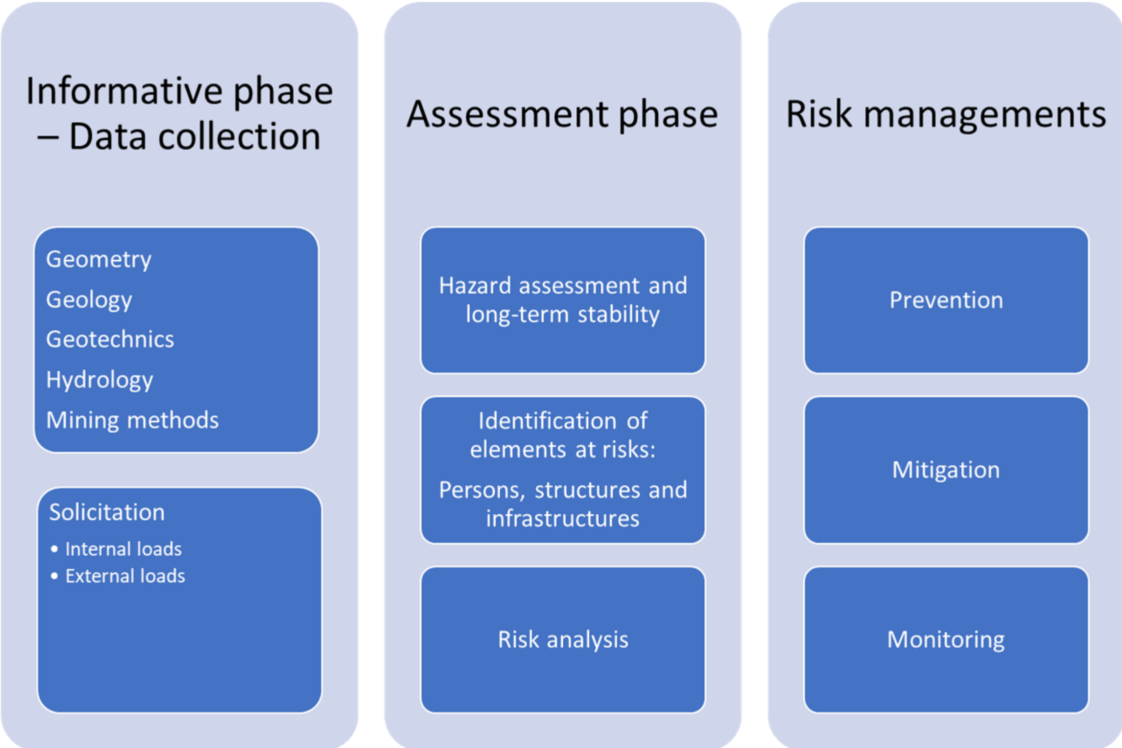


Figure 1. Schematic flowchart of the risk analysis of coal mine closure

The principle of qualification of the hazard consists in combining the criteria characterizing the intensity of a hazardous phenomenon with those to characterize the corresponding class of predisposition of the site studied (Figure 2). The principle of mining hazard qualification consists of two steps:
First step: the assessment of the sensitivity of the site (predisposition)
Second step: the assessment of the intensity of the phenomenon

3.2.1 Qualifying predisposition classes

Qualification of a predisposition consists of an analysis of the possibility that a phenomenon will appear or manifest on the surface, this definition is very close to the probability of occurrence of a natural hazard. This analysis is based first on experiential feedback, meaning 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 favorable 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.

3.2.2 Qualifying the intensity classes

The intensity of a phenomenon 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 of a sinkhole, water level of flooding, nature and content of gas emissions), but also their potential effects on people and goods.
Intensity classes are necessary to categorize potential damages or nuisances based on the nature of the phenomena. The approach to evaluating the intensity of a phenomenon consists of identifying the most representative physical parameters in order to characterize the consequences of potentially dangerous events. Thus, one can choose whether 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) and property (damages).
The number of intensity classes used for analysis may vary according to the context of the study and especially the accuracy and exhaustiveness of the input data. Hazard studies conducted in the context of mining risk prevention use the following classes to define: a phenomenon's intensity:

- 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).

The number of the hazard classes varies from one hazard to another: at least 3 (low, moderate, and severe) up to 6 (null, very low, low, moderate, severe, very severe). In this report, 3 classes are adopted. When we have more than three, we regrouped them and presented only 3 classes. The matrix of hazards is generally used to present the intersection between the intensity and the predisposition (Figure 2).

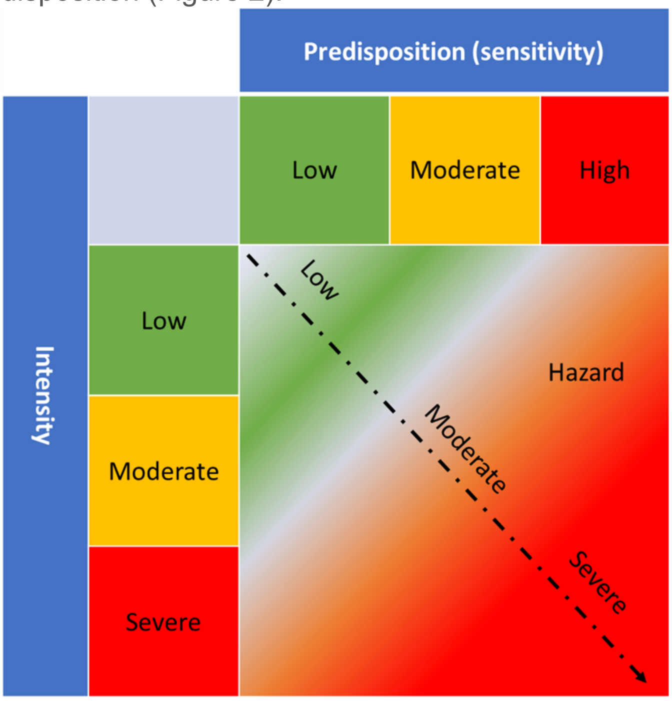


Figure 2. Hazard class based on the sensitivity (predisposition) and intensity classes for mining hazard assessment

4 Multi-hazard analysis

4.1 Introduction

The post-mining activities in the EU should consider the environmental, social and economic impacts. The multi-hazard analysis should respond to the objectives of European directives, industrial directives, mining west directive, environmental liability directive.

Generally, an urban space faces more than a single hazard, but a set of hazards in interactions. However, current risk management is based on single hazard and that presents a serious issue. By considering the risks associated to hazards separately, the solutions provided for their management generally do not consider other phenomena and are sometimes even incompatible with the latter (Touili, 2018). The impact of hazards can be due to a single variable being in an extreme state, but more often it is the result of a combination of variables not all of which are necessarily extreme. Here, the combination of variables or hazards that lead to an extreme impact is referred to as a compound hazard: multi-hazards.

For a site exposed to several hazards, multi-hazard analyses, unlike single hazard analyses, consist in considering each hazard as an element in potential interaction with other hazards also identified on the site. This global and integrating approach which considers several hazards make it possible to represent as faithfully as possible the situations in which they coexist and interact on the same territory/site.

The interaction between hazards can relate to their “physical” (or phenomenological) occurrence, and/or to their regulatory transcription, which can lead to different or even contradictory management actions.

The ignoring interactions between important environmental and anthropogenic processes could distort management priorities, increase vulnerability to other spatially relevant hazards or underestimate disaster risk (Gill and Malamud, 2016). Lo Jacomo et al. (2017) present in Figure 3 an example of the hazard mitigations for one hazard and the negative consequences on the other potential hazards. For instance, the dam can protect the building from the flooding hazard, but that can increase the consequences of a large earthquake due to the collapse of the dam or/and trigger a seismic event. Another example concerns the consequences of allowing the construction near slopes to avoid the flooding in the valley, etc. Consequently, the mitigation solution can be the causes and the trigging of another hazard.

For mining context, such situations can be met. For example, allowing the vegetation of dumps to reduce the slope instability can increase the risk of the fire, considering the risk of combustion of the residual coal.

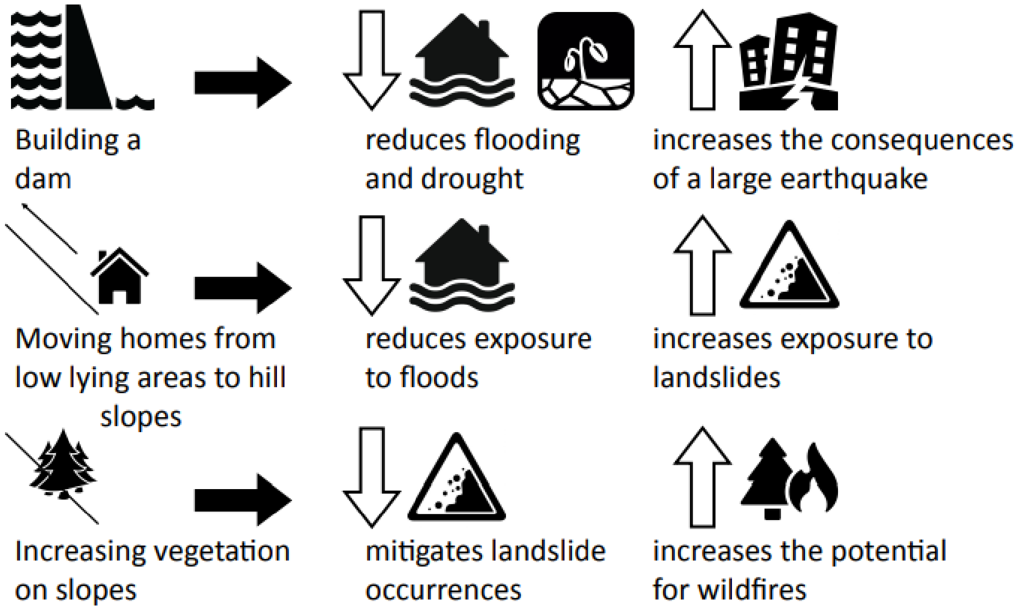


Figure 3. Consequences of mitigations on multi-hazard (Lo Jacomo et al., 2017)

Thus, the multi-hazard risk assessment allows the optimisation of the mitigation solutions and consequentially the social-economic benefit.

4.2 Definitions

Different definitions of multi-hazard events exist. Hazard relations or hazard interactions refer to any kind of connection, mutual influence, or spatial or temporal coincidence between hazards. The terms hazard relationships and hazard interrelations are used synonymously (Kappes et al., 2011, 2012, Gill et Malamud, 2014, 2017, UNDRR, etc.).

The European commission (2010) defines the multi-hazard as following: to determine the probability of occurrence of different hazards either occurring at the same time or shortly following each other, because they are dependent from one another or because they are caused by the same triggering event or hazard, or merely threatening the same elements at risk without chronological coincidence.

For the British Geology Survey (BGS, Ciurean et al., 2018), the definition of multi-hazard is assumed as meaning (1) the selection of multiple major hazards that a country faces, and (2) the specific context where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects (UNISDR, 2017). There are different types of 'interrelated effects' described by UNISDR (2017) presented in the § 4.4.

4.3 Advantages and limitation of multi-hazard analysis

Separate hazard/risk management increases the cost and decreases the effectiveness of interventions. A single hazard (risk) management can lead to a distortion of the management priorities, an increase of vulnerability for other spatially relevant hazards, or an underestimation of risk (Gill and Malamud, 2014). 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. Therefore, it appears increasingly necessary to consider risks in a "global" approach, whereas mine managers and local authorities often manage only single hazards. Interest in multirisk assessment has increased during 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].
Regarding 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 multirisk analysis, which considers several hazards and associated vulnerabilities, better represents situations for which 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 likely to lead to regulatory contradictions. Multirisk assessment tools can support decision-makers and provide them with information on mitigation measures [15].
The multi-hazard approach allows also to minimise the socio-economic negative and to maximise the positive impact of the post-mining hazards and reuse of mining land.
One of the advantages of multi-hazards and multi-risk approach is the increasing the resilience of the regions exposed to several hazards and reducing the errors of the decision-makings.
The multi-hazard and multi-risk assessment allow to give wight for the different potential scenario of the hazard's interaction.
The multi-hazard assessment allows to increase the resilience of the regions impacted by several hazards.

4.4 Assessment of the multi-hazard methodology

The assessment of the multi-hazard depends on the qualification of the potential interaction between signal hazards. The interaction of identified hazards depends on the trigger hazards (Gill and Malamud, 2016). The general framework of the multi-hazards and multi-risk assessment is developed by Liu et al. (2016) for natural hazard interaction and presented in the Figure 4. The framework comprises steps for hazards and risk assessments. We focus more on the hazards interaction assessments. The method can be used for the mine hazard interaction. The last two steps concern the WP3 and WP4 of the POMHAZ projet.

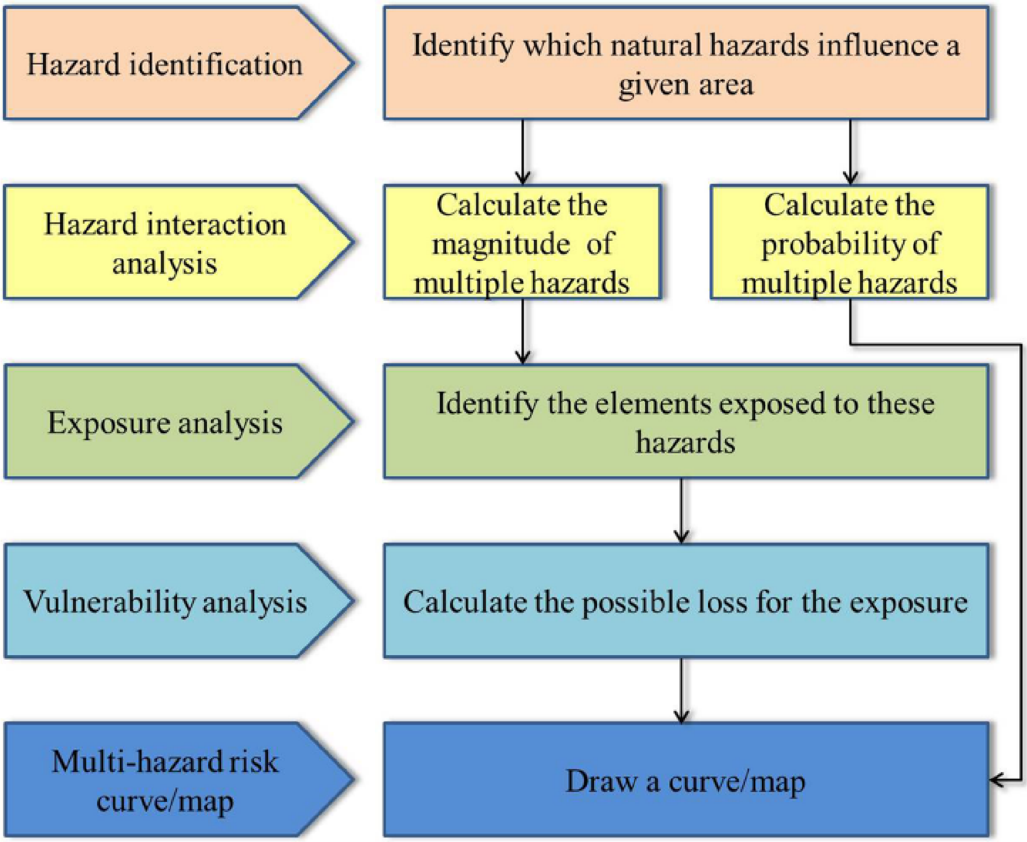


Figure 4. General framework of a multi-hazard and multi-risk assessments (Liu et al., 2016)

In the post-mining site, globally, we can take in consideration not only the mining hazards but also the natural and technology hazards. The adopted methodology of the multi-hazard assessment in the post-mining is divided into four main steps (Figure 5):

The first step describes the three significant hazards families: mining, natural, and technological. The multi-hazard interaction follows the single hazard identification described in the chapter 5.

The second step of the analysis is the identification of 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 third important step is the description of the interactions. At this stage we should identify if the interaction is triggering, aggravating, and cascading (domino). Additionally, the interaction of hazards can have a regulatory impact. However, the regulatory interaction is very specific topic due to the different laws in the different European countries. Thus, we limit the work to the identification of the physical interaction description. In this step, the level of interactions between hazards should be assessed. The level of the interaction is based on the intensity of the single hazards and the level of the interaction. of the potential interaction using matrix interaction tool and/or the interaction network (Bayesian network) tool. The final (fourth) step concerns the visualisation (mapping) of the interaction of the hazards. Specific indicators can be used for the visualisation of the level and the type of the interaction.

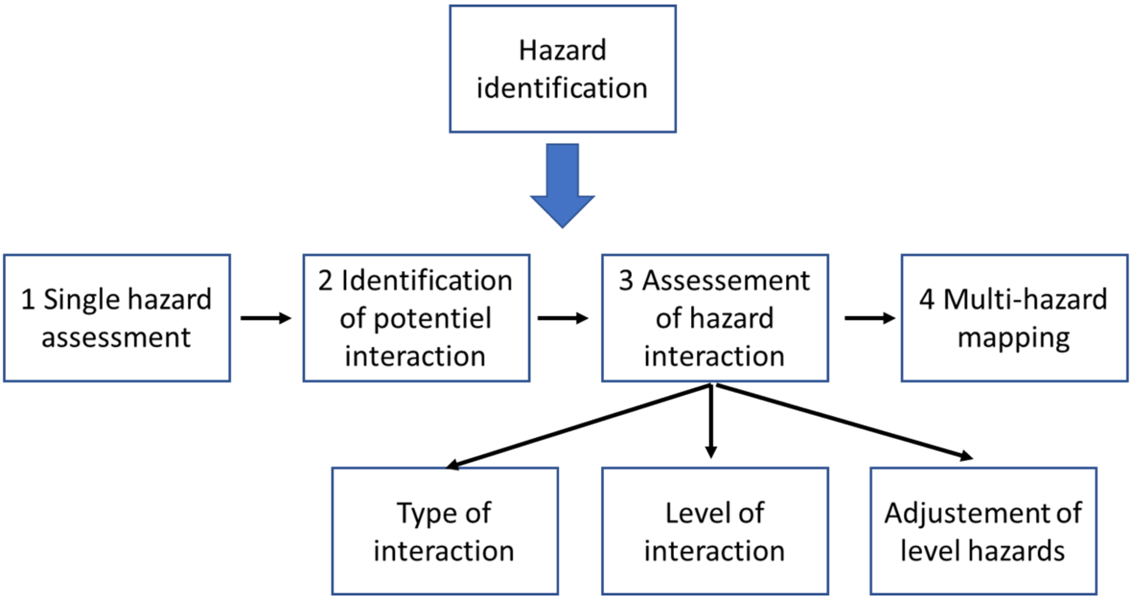


Figure 5. Main steps of the multi-hazard assessment methodology from a single hazard to multi-hazards

The assessment of the hazard interaction (step 3) can be carried out through asking the following questions by the experts in charge of study:
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 or the predisposition of the site: which parameters should modify the target probability of occurrence of the phenomenon or the predisposition factors?
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?
The third step also should identify the scales of the interaction between mining, natural and technology hazards: spatial scale and temporal scale. The spatial scale interaction can cover very limited surface (very local) to large surface (regional land). The temporal scale covers very short event, hours, to very long period (years). For instance, certain mining hazards as ground movement are very local and very short (e.g.: a sinkhole hazard). On one hand, the flooding hazard can be very local (flooding due to the failure of water supply network) or regional (heavy raining). 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).
Additionally, this step concerns the adjustment of the initial hazard level. After the identification and the description of the hazard interaction, an adjustment of the level of hazards is mandatory.

In the case of studied area is exposed to multi-hazard, three physical potential interactions should be verified (Figure 6):
• Coupled or combined dependent contingencies. The area is subject to several hazards having the same trigging factors and / or initiating events. Their consequences are cumulative over the same study area. In this case, a hazard can trigger one or more hazards; there is a direct causal link between one and more hazards occurring consecutively in a territory.

• Sequential dependent hazards (at the same time). The hazard modifies the conditions of one or more hazards. When a hazard occurs, the conditions for the occurrence of a second hazard may meet, the area becomes more willing, or the probability of occurrence is greater. The second hazard is completely or partially dependent on the first.

• Dependent hazards (shifted in time). The occurrence of a first hazard triggers, amplifies, or alters the second and so on. It is a chain reaction of several hazards. The dependent hazards can lead to a domino or cascade effect (de Ruiter et al., 2020). Domino effects prolong the diffusion of consequences in space and time beyond the scale of the hazards taken independently (van Westen et al., 2014). The cascade is observed when the second hazard result from the occurrence of the first hazard (Liu et al. 2015), for instance, the flooding of the Orléans region (France) induced the collapse of underground cavities (Noury et al., 2018).

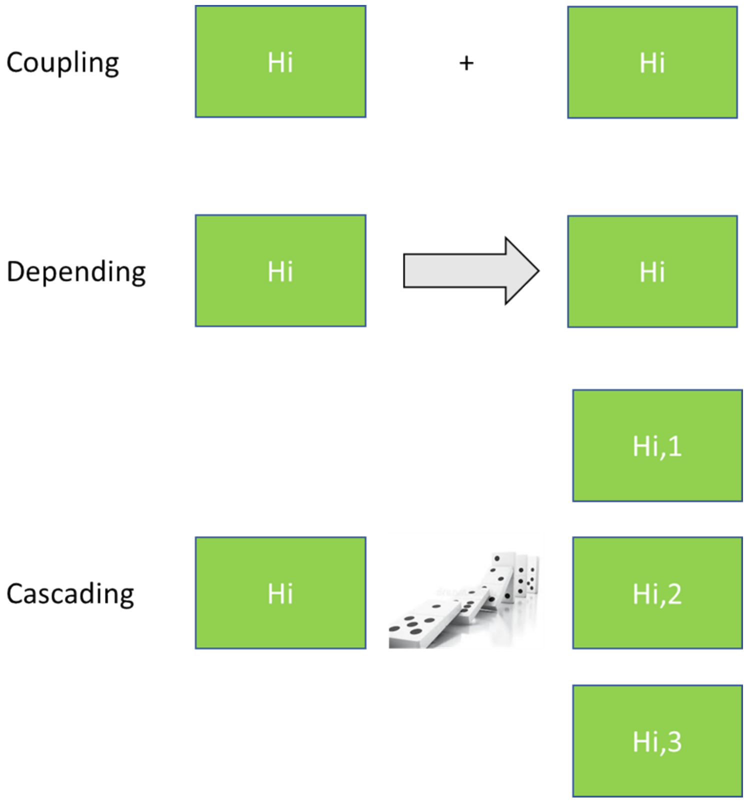


Figure 6. Different types of hazard interaction: coupling, depending on and cascading

4.5 Methods and tools

Different approaches and tools can be used for describing and identifying the hazard interaction. Cirurean et al. (2018) present three methods: qualitative, semi-qualitative-quantitative and quantitative methods. Based on the three main categories, we can list the following approaches:

- narrative Descriptions (Qualitative)
- hazard Wheels (Qualitative)
- hazard matrices (Qualitative/Semi-Quantitative)
- network interaction/flow diagrams (Qualitative/Semi-Quantitative)
- development of Hazard/Risk Indices (Semi-Quantitative)
- systems based on Physical Modelling (Quantitative)
- probabilistic and Statistical Approaches (Quantitative)

The first approach (narrative description) is the easiest one and based on the feedback of the experts and the in-situ observations. On the other hand, modelling (numerical and physical) and probabilistic approaches are the sophisticated ones, need generally enough input and data.
To analyse the potential consequences of series of events, the event trees proved useful assessment (Eshrati et al., 2015), although their elaboration is extremely demanding. First, a triggering event is defined and secondly, known possible subsequent incidences are identified and arranged in a tree-structure. Different event-tree-like or fault-tree-like strategies can be used in order to exhaustively identify a complete set of scenarios (Garcia-Aristizabal et al., 2015).
The ARMONIA project (Delmonaco et al., 2006) discussed the development of syntactic indicators of multi-hazard based on the number of hazards affecting a site or district. Another approach was developed on the basis of the overlay map of the different hazards. The syntactic indicators can be presented by a single multi-hazard map. For attempting such map, a homogenisation of the intensity scale is necessary to be able to define one indicator.
The assessing of the multi-hazard and risk is based on input parameters for the individual hazards. There is a real need to harmonize existing methodologies on data collection and databases across the European countries (Komendantova et al., 2014). Thus, the multi-hazard assessment requires proven expertise (Chen et al., 2016, Gill et al., 2020).
Lo Jacomo et al., (2017) propose two steps for a multi-hazard assessment: developing the model and the application of the model. The first step is based on the hazards identification and interaction assessment and then the carrying out of a sensitivity study to identify the critical parameters. The second step is the application of the model on a real case study.

Liu et al. (2015) consider that the method of the analysis depends on the level of the analysis. They consider three levels of multi-hazard assessment (Figure 7): level 1: qualitative risk analysis, level 2: semi-quantitative multi-risk analysis and level 3: quantitative multi-risk analysis.

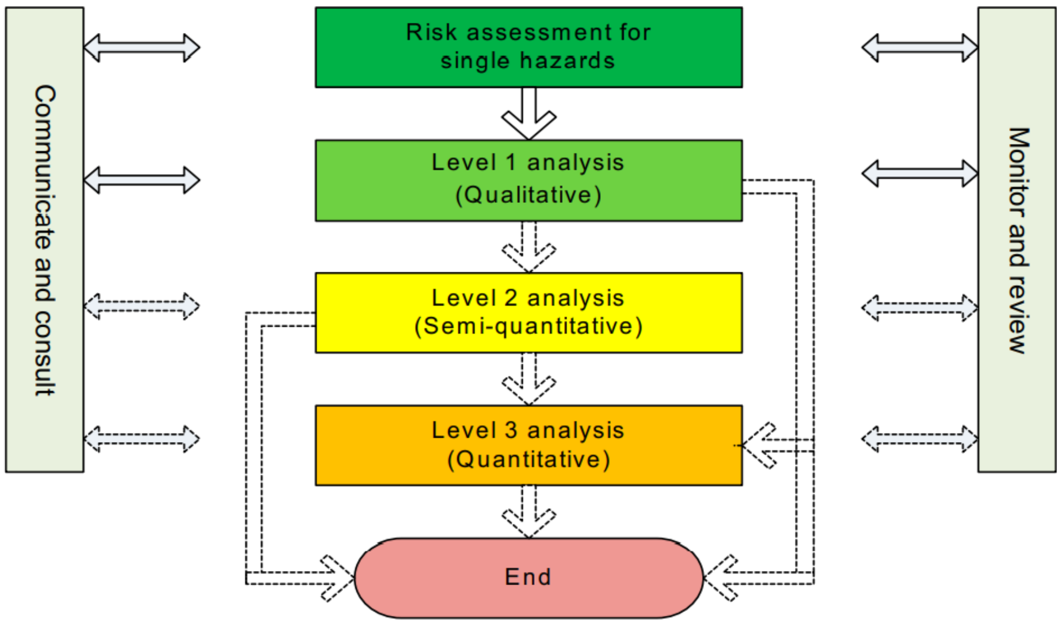


Figure 7. Multi-risk assessment framework (Liu et al., 2015)

4.5.1 Multi-hazard matrix interaction

Multi-hazard interaction matrix is a qualitative method. Kappes (2011) reviewed the use of the interaction matrix for assessing the interaction between hazards. The approach is based on the system theory for which the system is a group of interacting. The basis of this approach consists of the comprehension and description of the relationships among agents and processes in the evolution of the system. It offers a semi-quantitative and structured approach to examine and visualize hazard interactions (Gill et Malamud, 2014). Experts encode all possible relations among hazards into a matrix. Multi-hazard risk is then estimated by overlaying all spatial information consecutively. Figure 8 shows interaction matrices for compound and cascading risks separately. The interrelation matrices can be developed on the basis of literature review and expert knowledge on the possible interactions between hazards. The multi-hazard matrix is very useful for identifying the potential interaction between hazards (Figure 8). Multi-hazard interaction matrix identifies the influence of hazard Hi on hazard Hj. It also makes it possible to specify the type and level of interaction thanks to a system of notes or codes. The hazard in the line causes and the hazard in the column receives the influence. Gill et Malamud (2016) defined a primary hazard (initial hazards located in the n lines) can trigger secondary hazards (several). For instance, an earthquake can trigger a tsunami, a landslide, a snow avalanche, a flood, a subsidence, etc.

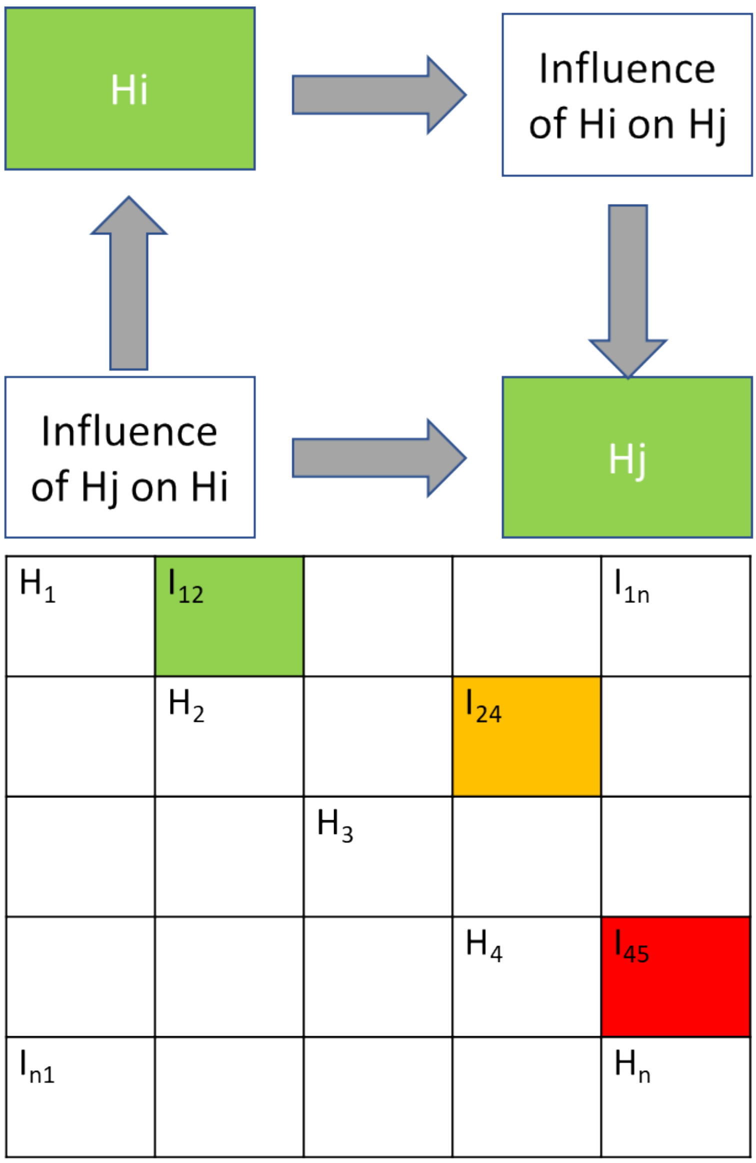


Figure 8. Hazard interaction matrix, the matrix presents the interaction between n hazards (H_n) and the I_{ij} describes the level of the interaction, green: low interaction, orange: moderate interaction, red: high interaction

Sigtryggsdottir et al. (2015) describe interrelation matrix for two systems of hazards (for instance, mining hazards and naturals hazards), comprising interrelations within each system as well as between them (Figure 9). System 1 is defined by the processes P1, P2, ..., Pn, while system 2 is defined by processes p1, p2, ..., pm. The interrelation of the processes within system 1 is described by a nxn interrelation submatrix in the upper left quarter of the two-system interrelation matrix. Similarly, the interrelation of the processes p within system 2 is described by an mxm interrelation submatrix in the lower left quarter of the two-system interrelation matrix. The number of processes defining the respective systems does not need to be equal.

System 1 | System 1 interrelation to System 2 (I_{Pp})

P_1	$I_{P\,1,2}$		$I_{P\,1,i}$		$I_{P\,1,n}$	$I_{Pp\,1,1}$		$I_{Pp\,1,k}$		$I_{Pp\,1,m}$
$I_{P\,2,1}$	P_2		$I_{P\,2,i}$		$I_{P\,2,n}$	$I_{Pp\,2,1}$		$I_{Pp\,2,k}$		$I_{Pp2,m}$
$I_{P\,i,1}$	$I_{P\,i,2}$		P_i		$I_{P\,i,n}$	$I_{Pp\,i,1}$		$I_{Pp\,i,k}$		$I_{Pp\,i,m}$
$I_{P\,n,1}$	$I_{P\,n,2}$		$I_{P\,n,i}$		P_n	$I_{Pp\,n,1}$		$I_{Pp\,n,k}$		$I_{Pp\,n,m}$
$I_{pP\,1,1}$	$I_{pP\,1,2}$		$I_{pP\,1,i}$		$I_{pP\,1,n}$	p_1		$I_{p\,1,k}$		$I_{p\,1,m}$
$I_{pP\,k,1}$	$I_{pP\,k,2}$		$I_{pP\,k,i}$		$I_{pP\,k,n}$	$I_{p\,k,1}$		p_k		$I_{p\,k,m}$
$I_{pP\,m,1}$	$I_{pP\,m,2}$		$I_{pP\,m,i}$		$I_{pP\,m,n}$	$I_{p\,m,1}$		$I_{p\,m,k}$		p_m

System 2 interrelation to System 1 (I_{pP}) | System 2

Figure 9. Two-system interrelation matrix. The processes P1, P2, ..., Pn define system 1, and the processes p1, p2, ... , pm define system 2. Ip and IP describe interrelations within the respective systems, while IPp and IpP describe interrelations between the two systems (Sigtryggsdottir et al., 2015)

4.5.2 Network interaction (Bayesian network)

The network interaction (Bayesian network) is used for assessing the interaction between hazards and external factors. The Bayesian network allows to represent the interaction between hazards. This tool provides the core of the multi-hazard impact framework. A hazard or risk manager can use this network interaction in the 'preparedness' phase of disaster risk management. It will help the user to identify which potential scenarios they might face and to

prioritise which cases to investigate further to better implement an effective disaster risk reduction strategy.
Such a network interaction would be useful to visualise the potential scenarios of cascading events.
Therefore, the network can indicate the direction of the interaction, the type of the interaction and identify the potential scenarios. The types of interrelations are displayed by the colour of arrows. When two hazards can be interrelated with two different interrelation types (e.g., a landslide can either trigger or change conditions for river flood), the filling and the outside line are from two different colours. Arrows are used to represent the direction of the "hazard cascade" when relevant (i.e., triggering and change conditions interrelations). These are a geographical representation of the upper part of the influence diagram, the hazard and environment susceptibility, for all the hazards.
The network interactions display hazards as nodes and the lines linking them as various occurring relationships. Concurrently, the authors argue for the conceptualisation of hazards through their potential to trigger or be triggered by other hazards. This is especially important in decision-making scenarios as it represents a tool for forecasting secondary hazard potential, spatial overlap and temporal likelihood based on the triggering event.
The Figure 10 presents an example of the interaction network for three hazards (H1, H2 and H3). Each hazard is assessed based on the factors related to the phenomenon and the predisposition of the site. The interaction between the three hazards can be double interaction: H1 can trigger H2 and H2 can trigger H1. The level of the interaction is high (red) for H1-H2 and low for H2-H1. A cascade (domino) interaction can also be identified between H1-H2 and H3. Different scenarios can be described: H1 can trigger H2 and H2 can trigger H3, or H1 can trigger H2 and H3. The result of the interaction network is the number of the interactions, the types of the interactions and the potential interaction scenarios.

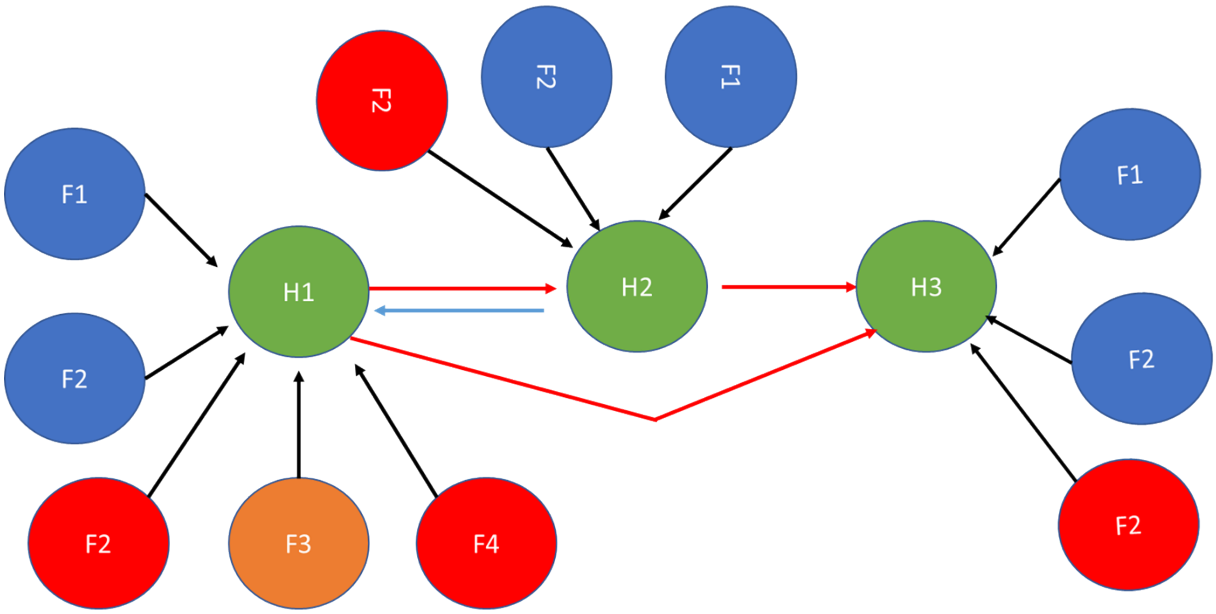


Figure 10. Network interaction, interconnected network, of three hazards (H), each single hazard is assessed using the intensity qualification (F1 à FN) and predisposition of the site

4.5.3 Event-tree and Fault-tree approach

Fault tree analysis (FTA) and event tree analysis (ETA) are two powerful techniques for identifying and evaluating hazards and risks in complex systems. An event tree is an inductive analytical diagram in which an event is analysed using Boolean logic to examine a chronological series of subsequent events or consequences. Fault tree analysis (FTA) is a type of failure analysis in which an undesired state of a system is examined.

To analyse the potential consequences of series of events, the event trees proved useful assessment (Eshrati et al., 2015), although their elaboration is extremely demanding. First, a triggering event is defined and secondly, known possible subsequent incidences are identified and arranged in a tree-structure. Different event-tree-like or fault-tree-like strategies can be used in order to exhaustively identify a complete set of scenarios (Garcia-Aristizabal et al., 2015).

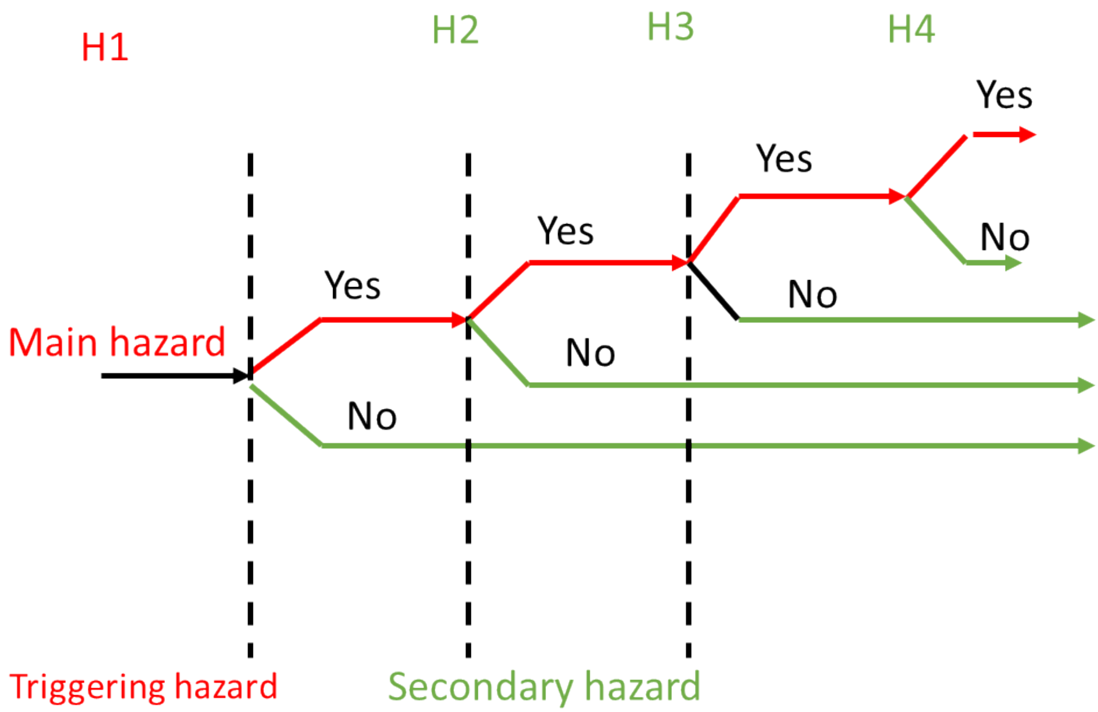


Figure 11. Fault tree for several hazards (H1 to H4) in which the main hazard can trigger several secondary hazards sequentially.

4.5.4 Modification of the initial hazard level

A simple Multi-hazard Index was suggested by Dilley et al. (2005). It corresponds to the sum of the hazard's value. Only the high hazard class is taken into account, adding up the values of all overlapping hazards within a pixel. The result is given as a number of hazards affecting each pixel.

Odeh Engineers Inc. (2001) computes continuous Hazard Scores (HS). The HS are calculated at a subregional level, that is, for communities as a whole (instead of modelling hazards in a distributed way, pixel by pixel) according to the following equation:

$$HS = FS \times AIS \times IS$$

with:
FS Frequency Scores: measuring how often a given hazard occurs [events per year, classified in five levels],
AIS Area Impact Score: measuring the extent of the geographical area that potentially will be affected by a hazard event [gross or relative area, classified in five levels],
and IS Intensity Score: measuring the intensity level of a hazard [hazard-specific units, classified in five levels].

The resulting HS is a continuous measure can be compared for one region. This thus indicates the importance of each hazard and in addition allows for the comparison between communities.

The next step, after the identification of the interaction between hazards, is the updating of the intensity of the initial hazards and calculating an indicator for the multi-hazard. The simple way to determine a multi-hazard or risks indicator (MHRI) is based on the sum of the individual hazard or risk value. This approach is used by Tiepolo et al. (2018) to compare several regions exposed to pluvial flooding, fluvial flooding, and drought hazards.

$$\text{MHRI} = \sum H * V$$

Where:
H the hazard and V the vulnerability of the elements at risk…
This indicator (MHRI) can be used for different sites to compare the hazards and the risks.
Another approach is based on the adjustment of the initial hazard level. To adjust the initial hazard level, Liu et al. (2021) suggested the following method, 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).

Table 1. Adjustment of the initial hazard based on the method suggested by Liu et al. (2017)

Primary hazard situation	Intensity degree of primary hazard	Adjustment principle
For hazard that needs adjustment, there is no primary hazard that induces its occurrence	–	Adjusted intensity degree = Initial intensity degree × 1
For hazard that needs adjustment, there is a primary hazard that has a high probability to induce its occurrence	5	Adjusted intensity degree = Initial intensity degree × 1.5
	3–4	Adjusted intensity degree = Initial intensity degree × 1.4
	1–2	Adjusted intensity degree = Initial intensity degree × 1.3
For hazard that needs adjustment, there is a primary hazard that has a low probability to induce its occurrence	5	Adjusted intensity degree = Initial intensity degree × 1.3
	3–4	Adjusted intensity degree = Initial intensity degree × 1.2
	1–2	Adjusted intensity degree = Initial intensity degree × 1.1

Based on this statement, we adopted the same method for the mining-mining hazard interaction and mining-natural hazard interaction. Table 3 presents the initial hazard level and the adjusted hazard. Three level of interaction are considered (low, medium, and high).

Table 2. 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

To calculate a multi-hazard indicator, we suggest the following indicator representing the sum of the cumulate of the adjustment hazards values. Therefore, the final multi-hazard intensity can be calculated by summing up the adjusted intensity degree of every single hazard as shown in Eq. (1).

$$MH = \sum_{i=1}^{n} Hai$$

where, Hai represents the adjusted intensity degree of hazard i, 1, 2, … n; and MH represents the multi-hazard intensity.
The multi-risk can be calculated from the following equation:

$$R = \sum_{n=1}^{n} (R_i)$$

With Ri is the individual risk assessment: $R_i =$ Hi * Vi
Hi: the individual hazard level
Vi: the individual vulnerability class

Another method can be used to present the level of interaction: this method is called an interaction index. The interaction index is calculated between one hazard related to n existing hazards. It was developed to assess the potential of the interaction between hazards. High score indicates a high potential interaction between existing hazards.
H_I = 2*Isc * n (n -1), the 2 corresponds to the columns and rows of the matrix.
We can calculate the maximum value (Hmax) of the score for n hazard(s). The maximum interaction value is 3 and Hi, max=2* 3 * n (n -1) = 6 n*(n-1).
where n is the number of hazards, and H_I is the hazard interaction index. The maximum interaction index (Hi, max) corresponds to Isc equal to 3 for all hazards.

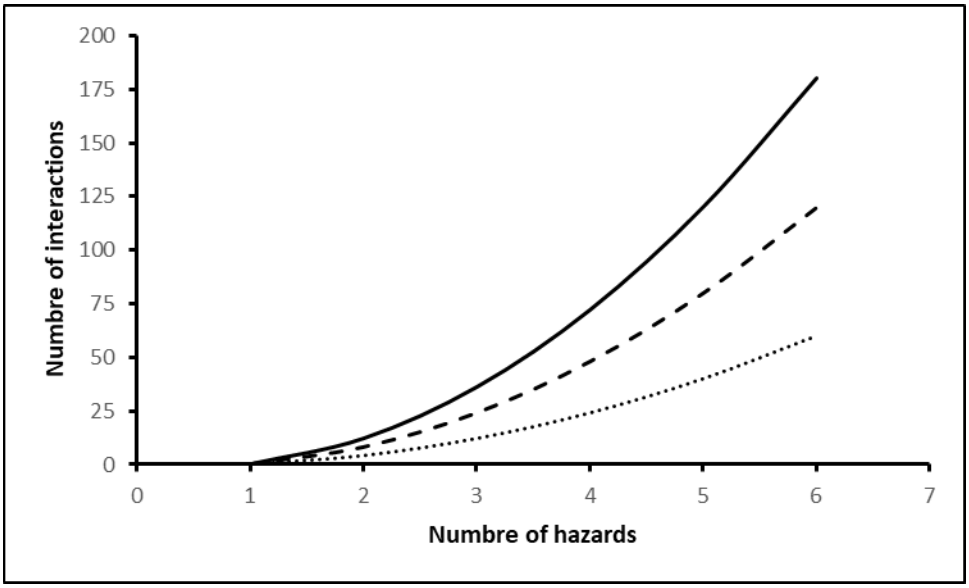


Figure 12. Evolution of the number of interactions as function of the number of hazards and the level of interaction, low, moderate and high

Certain software's were developed for calculating the multi-hazard interactions and the assessment at different scales, such as Hazus-MH (Delmonaco et al., 2006, van Westen et al., 2014). The version dealing multi-hazard has been available since 2017. Three hazards are integrated: wind, earthquake and flooding. The software is coupled with GIS technology.
Gill and Malamud (2014) have developed a method, calling the Overlap-likelihood factor (OLF) to represent the interaction between hazards temporally and spatially, three classes for the spatially interaction (limited, medium, and large) and three classes for temporally interaction (low, medium, and high). The two parameters create 9 configurations (limited-low, limited-medium, limited, high, …., large-high) that can be replaced by numbers: 1, 2 and 3 for spatially classes and 1, 2 and 3 for temporally classes. According to the last suggestion, classes of OLF vary from 1 to 9. The OLF can be calculated for n hazards.

4.5.5 Mapping of the multi-hazard

Mapping the hazards and the risk at a mine is an important step to show information about hazards, vulnerabilities and risks in a particular area and thereby support the risk assessment process and overall risk management strategy. They can help set priorities for risk reduction strategies. Maps also have important roles to ensure that all actors in risk assessment have the same information about hazards and in the dissemination of the risk assessment results to stakeholders. Finally, risk mapping could also be useful in the broader context of land use planning.

The European commission (2011) defines the multi-hazard map by: a map that portrays levels of probability of several hazards occurring across a geographical area. Kappes et al. (2012) present three mapping approaches:

- firstly, the visualization of each single hazard/risk separately,
- secondly, the reduction in the multi-dimensionality to visualize a combined hazard or risk, variable such as the overall hazard or risk,
- and thirdly, the presentation of more than one process displayed in one map.

The concept of a virtual city was also suggested to visualise for the stakeholders the presence of several hazards in the same space (Komendantova et al., 2014).

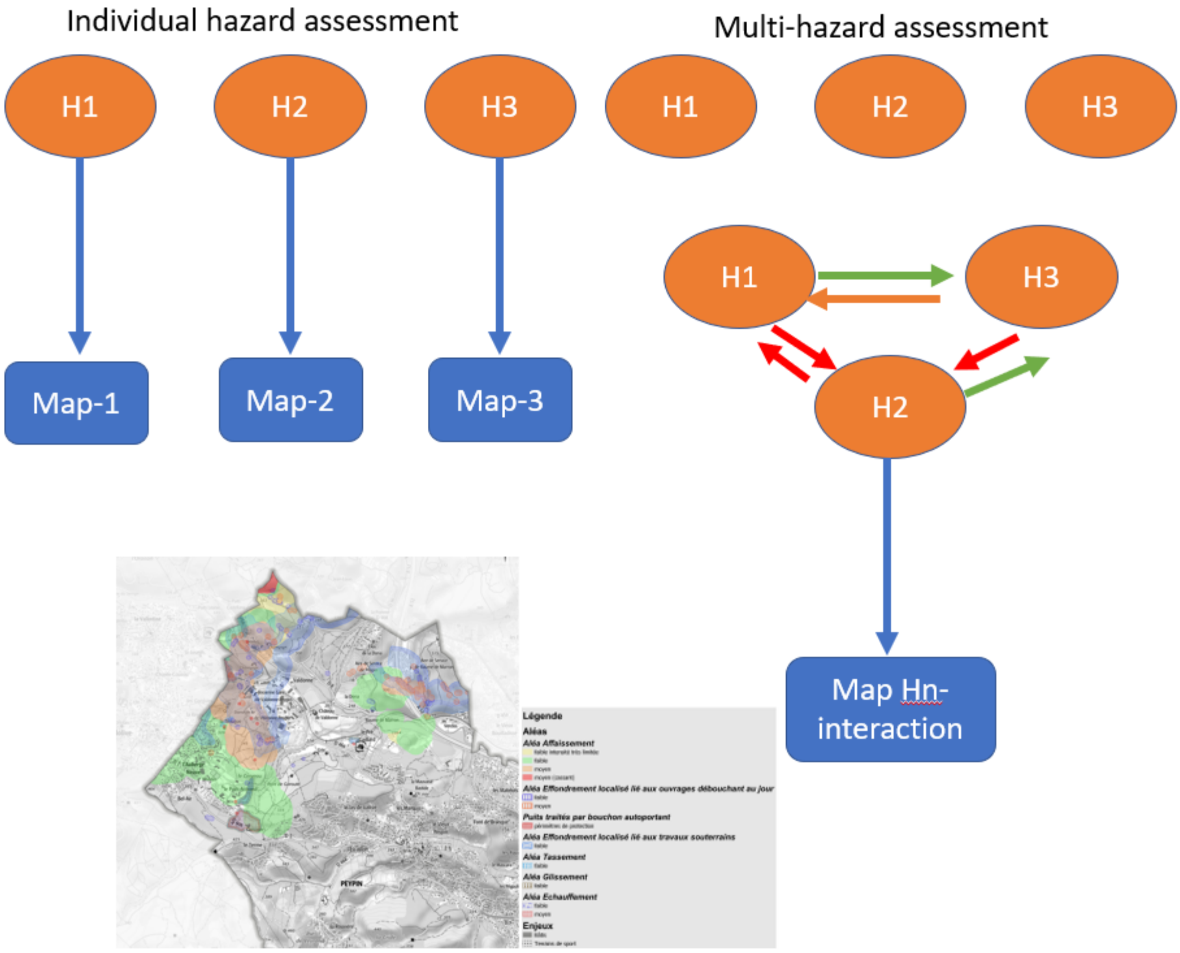


Figure 13. Two mapping approaches: individual hazard assessment and multi-hazard assessment

5 Post-mining hazards assessment for European countries

5.1 French experience

In France the following hazards are considered for the post-mining risk assessment analysis:

1- Ground movement: 1.1 Sinkhole (underground mines), 1.2 Subsidence (underground mines), 1.3 Massive mine collapse (underground mines), 1.4 Crevice (underground mines), 1.5 Settlement (underground mines, dumping areas), 1.6 Landslides (dumps, open pit mines), 1.7 Rock falls (open pit mines)
2- Combustion -self-heating (shallow mines, waste embankment)
3- Flooding (underground/surface/open pit lake)
4- Gas emissions (underground)
5- Radiation (underground)
6- Water and soil pollution (underground/surface and pit lake only for water)

5.1.1 Methodology of hazards assessment:

The hazards (the undesired phenomenons) assessment is based on a combination of predisposition and intensity. To assess a single mining hazard two stages are carried out:
• an "information" stage consisting of a description of the mining sites being 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 evaluate the hazard. At the end of this stage, one or more informative maps are produced.
• a hazard evaluation stage that defines, for each phenomenon identified as being relevant to the sites being 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 being studied.
The hazard study report brings these two stages together. In the mine conditions, three steps are required to qualify the mining hazard:

- Qualification of the intensity of the hazard,
- Qualification of the predisposition and the determination of hazard level assessment is obtained by crossing the hazard intensity and the predisposition factors.
- Qualifying intensity classes

The approach developed in France (Salmon et al., 2019) to evaluate the intensity of a phenomenon consists of identifying the most representative physical parameters in order to characterize the consequences of potentially dangerous events. Thus, one can choose whether 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) 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 conducted in the context 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).

5.1.1.1 Qualifying predisposition classes

Qualification of a predisposition consists of an analysis of the possibility that a phenomenon will appear or manifest on the surface. This analysis is based first on experiential feedback, meaning 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 related to 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.

5.1.1.2 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 1), 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 3. Mining hazard qualification based on the qualification of the predisposition and the intensity qualifications

Intensity	**Predisposition**		
	Unlikely	**Likely**	**Highly likely**
Low			
Moderate			
High			

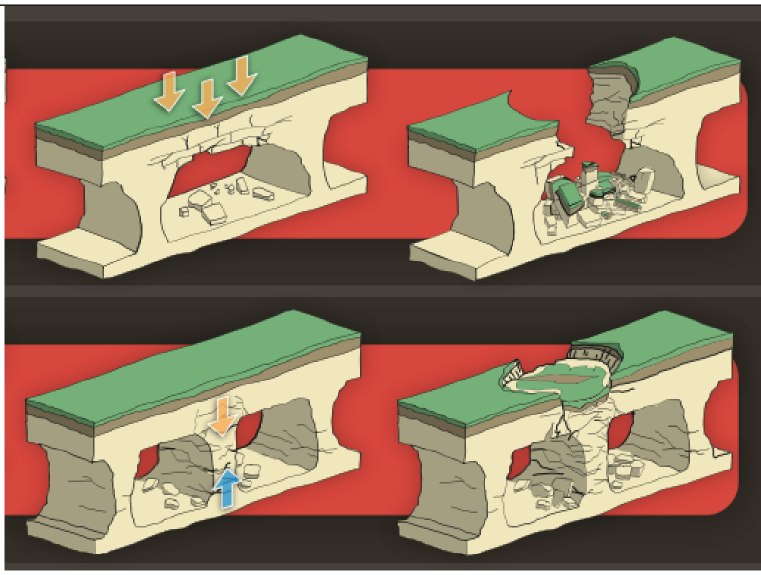
Below, there is an example for sinkhole. A national guideline can be used to assess the mining hazards (https://www.ineris.fr/en/post-mining-hazard-evaluation-and-mapping-france)).

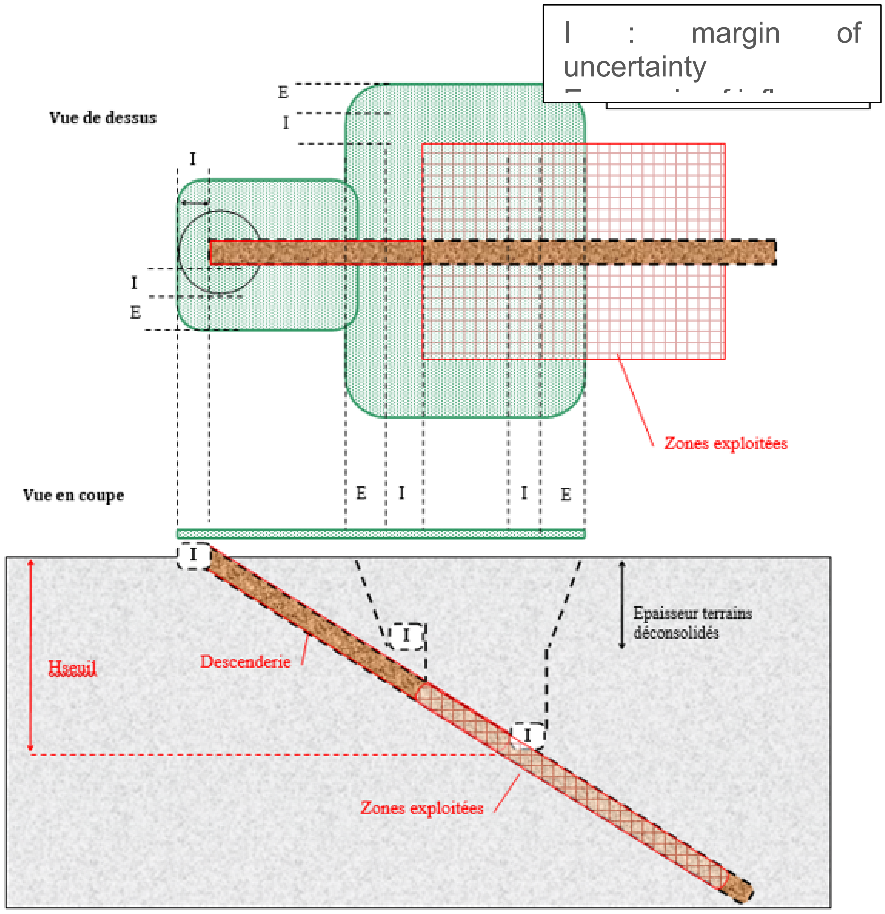
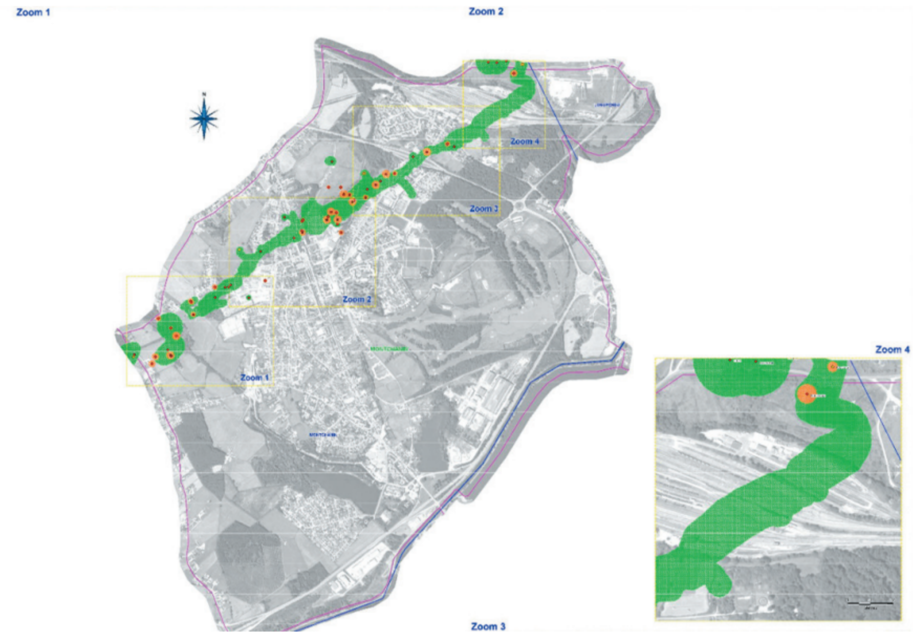
After the identification of the main hazards, in France, a monitoring program of the sites presents a specific risk. Operational monitoring missions were assigned to BRGM, which created a department dedicated to this purpose, the Mining Prevention and Safety Department (DPSM). The DPSM was entrusted with the following main missions:

- security work as delegated project owner.
- interventions following an expropriation measure.
- monitoring of mining site structures, under the Mining Code or the Environmental Code
- management of the post-mining information system, including management of intermediate technical mining archives and support for mining intelligence.

Table 4. Example of hazard assessment – France

Name of hazard	Ground movement – Sinkhole

Type of mine	Underground mine with residual voids
Phenomenon description	Because of the rock ageing, underground mine supports (rooms and pillar) deteriorate, leading to localized collapses on surface. It also could appear because of mine shaft.
Illustration	 Ineris figure
Criteria of predisposition (Probability of occurrence) (qualitative or quantitative)*	Depends on: • Presence of similar phenomenon on the site or in similar configurations, • Underground structure's predisposition to failure (width of gallery, characteristics of the primary roof beds), Failure of a gallery roof: very frequent (only when old mining cavities are less than 50 meters deep) • Failure of pillar: infrequent • Backfill run-out of mine shaft: frequent in very old shafts, especially during the mine water rising. • Mine shaft collapse: infrequent
Criteria of intensity (qualitative or quantitative)	Depends on collapse diameter: • Very low self-backfilled collapses in immediate proximity to the surface (centimetres in depth) • Limited Ø < 5 m • Moderate 5 m < Ø < 10 m • High Ø > 10 m
Cartographic area	The hazard map includes a margin of influence corresponding to the potential site coverage of the collapse crater and a margin of uncertainty (I) is added.

	  Example of hazard map – underground mining works shown in green and the sinkhole hazard is represented by an orange circular surface
Interaction with natural or technology hazards	We could suppose that sinkhole hazard can increase other natural and mining hazards such as: quarry sinkhole (considered as natural hazards in France) (high), landslide (low), flooding (medium), salt dissolving (medium), combustion (low), crevice (low), subsidence (low).

	And sinkhole is increased by flooding (high), seismicity (natural and induced: high), global collapse (high), subsidence (high), crevice (medium), combustion (medium), natural sinkhole (high), salt dissolving (high)

***:** qualitative and quantitative methods depend on the informative phase; this phase is before the hazard assessment phase.

5.1.2 Actors of post-mining management in the country

France has a large experience because the last closed coal mine was in 2004 (Lorraine coalmine). The management of post-mining is shared between different actors, each actor interacts continuously for the coal region in transition. The main actor is the government represented by the mining authorities (national and regional). The mining authority is supported by different national organizations such as Ineris, BRGM and Cerema. A specific support structure was also created in 2003 (GEODERIS, https://geoderis.fr/) for investigating, completing the mining hazards and preparing the hazard maps for abandoned mines including coalmines. Figure 14 represents the main actors involved in the management of the post-mining risks.

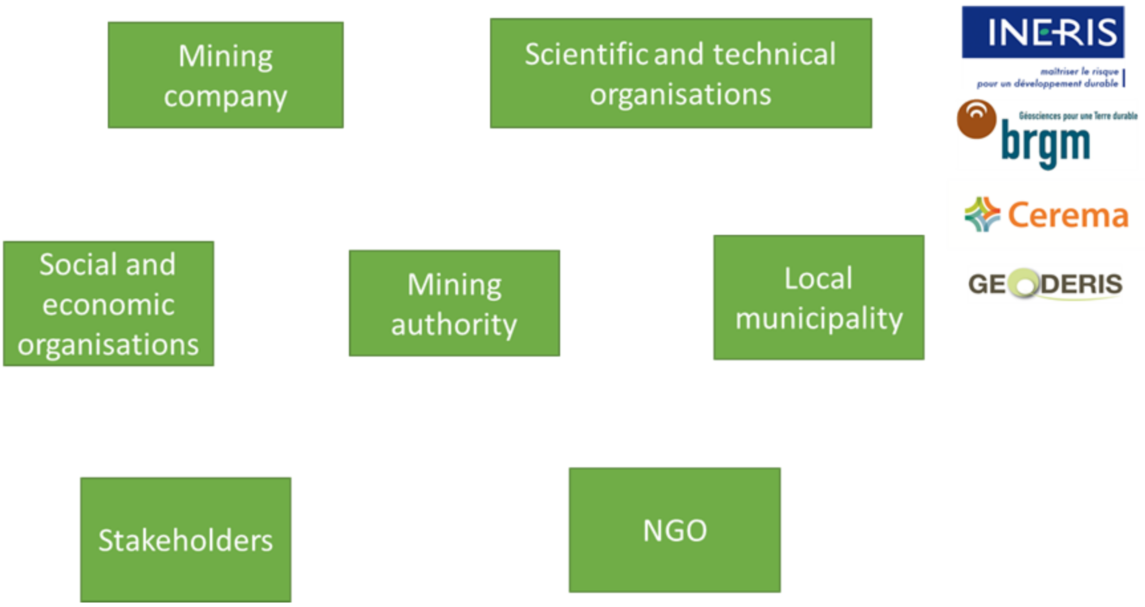


Figure 14. Main actors concerned by the management of the post-mining hazards and risks in France

5.1.3 Philosophy / actions of risks management

The French Mining code has regulated since 1810 the management of mines and post-mining activities. Normally, the mining companies must secure the closed mine after the declaration of the session of the mining activities to limit post-mining risks on population, structures, and infrastructures. They should plan, design, and execute the reclamation measurements. But for old, closed mines, it's not possible because reclamation works would be prohibitively expensive. French State has decided to apply a systematic prevention policy in order to identify potential harmful effects before they occur and thus to be able to prevent future accidents and social crisis. This policy represents a kind of "bet", assuming that the large amount of money invested in the prevention step will be cost-effective at long-term by reducing drastically victims and damages compensating costs. To apply this ambitious policy, the French mining legal scope has been considerably reinforced since 2000. Several major acts have thus been voted by French Parliament related to post-mining risk management.

Additionally, in order to identify, display and optimally manage the post-mining risk, the French State has acquired an effective technical and administrative tool: the PPRM (Plan de Prévention des risques miniers, meaning Mining Risk Prevention Plan, cf. Salmon et al., 2019). The primary objective of these plans is to identify the sectors likely to be affected, in the short or long term, by hazards of mining origin. They contribute also to draw up rules leading to sustainable development of the territory taking into account the various constraints linked to the post-mining period. The PPRM is an official urban plan document.
The procedure for drawing up a PPRM is initiated by a "prescription order" issued by the prefect (local national authority). This decree specifies the scope of the study as well as the nature of the risks taken into account and designates the decentralized State service which will be responsible for examining the file (“service instructor"). The prevention approach is, as far as possible, applied to coherent operating sectors in terms of predisposition to the development of disorders or nuisance. These physical units, called "risk basins", are delimited by natural parameters (geology, morphology, etc.) and/or exploitation (extension of work, etc.), and not by administrative boundaries (concessions, municipal territories).
The instructor service generally relies on one (or more) design office(s) to assist it in all or part of the various phases of the development of the PPRM, knowing that the regulatory phase remains under its direct management, under the responsibility of the prefect.
All the municipal councils of the municipalities for which the plan will be applicable is systematically requested for an opinion. The same goes for other organizations or administrations that may also be consulted depending on the nature of the risks studied. The draft plan is also submitted by the prefect to a public inquiry among the populations concerned. At the end of the various consultations, the PPRM, possibly modified, is approved by prefectural decree. It then becomes a public utility easement and must be appended to the PLU (Plan Town Planning Office), pursuant to Article L. 126-1 of the Town Planning Code.
In general, modifications or revisions to a PPRM are carried out according to the same procedure and under the same conditions as its initial development: prescription, elaboration, consultation, approval.

5.1.4 Multi-hazards approach

Not yet
The project POMHAZ will allowing the building of a methodology to consider the hazard’s interactions.

5.2 German Experience

In Germany the following hazards are considered for the post-mining risk assessment analysis:

- Ground movement: Subsidence, settlement, slope movement (generalized and local scale), rock falls, induced seismicity, sinkholes,
- Environmental pollution: Environmental water pollution, pollution from spoils and tailing dams,
- Hydrological issues: Hydrological disturbances (pit lake, surface and underground).
- Gas/Fire: Gas emissions linked to mining, combustion and overheating of mining waste.

5.2.1 Methodology of hazards assessment:

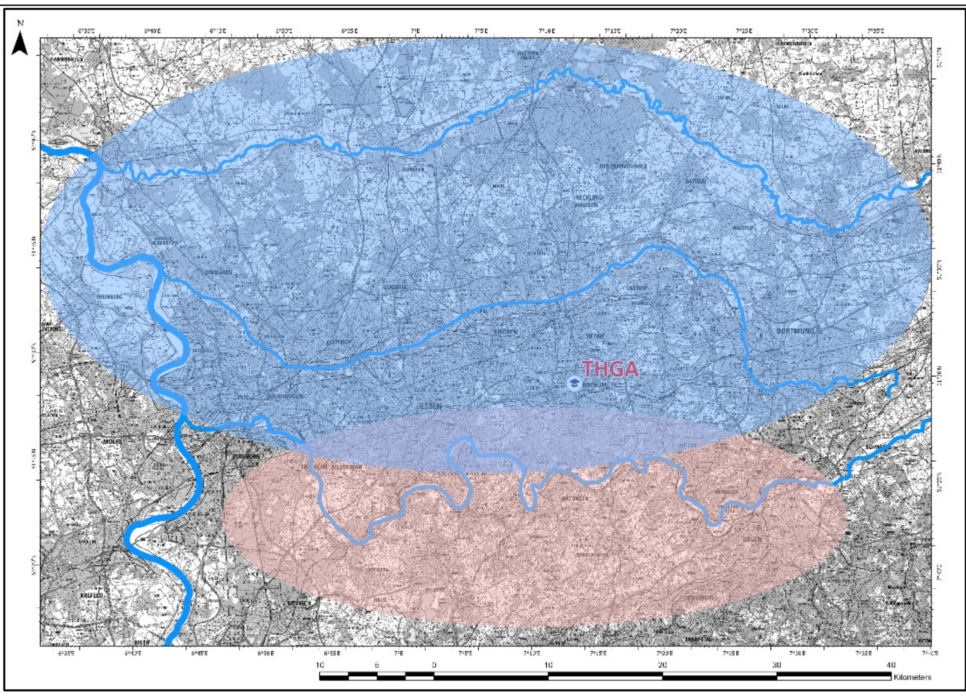
There are various recommendations for dealing with post-mining aspects. The German Mine Surveyors Association (DMV), for example, together with the German Society for Geotechnical Engineering (DGGT), has been operating a working group for years that regularly publishes recommendations for the investigation, evaluation, monitoring and rehabilitation of abandoned mines.
The way in which post-mining risks are dealt with varies from state to state, from mining sector to mining sector, from hazard to hazard, and from company to company.

5.2.2 PoMHaz case study Germany Ruhr area

An exemplary analysis and the many different parties involved are presented in the following chapters.

Table 5. Example of hazard assessment – Germany

Name of hazard	Multi-hazard environment: Subsidence, induced seismicity, sinkholes, environmental water pollution, hydrological disturbances, mining induced floods, gas emissions, combustion and overheating of mining waste.
Type of mine	Underground
Phenomenon description	Hard coal mining ended in 2018 with the closure of the last two mines in Bottrop and Ibbenbüren. There are tens of thousands of shafts in the Ruhr area, of which often neither the exact location nor the structural condition is known, especially in the southern area. The Ruhr region is divided in two parts with regard to post-mining risks at about the level of the A40 highway: In the overburden-free south, hazards such as sinkholes, gas emissions and hydrological disturbances (e.g., caused by dewatering adits) dominate due to near-surface mining. A special problem here is that mining at these adits has often left its traces for centuries and while not always sufficiently documented. Due to the strong dip of the coal-bearing strata to the north, mining here took place much later and much deeper. These areas are dominated by subsidence (in some cases over 30 m), the associated damage and polder areas. Temporary or permanent fires or hot spots can occur on many of the large mine dumps. In addition, mining-induced seismicity is still possible.
Illustration drawing	Principle sketch post-mining hazards in the Ruhr area, Bezirksregierung Arnsberg Abt. 6 - Bergbau und Energie in NRW (2021)
Criteria of predisposition (Probability of	Depending on the hazard and the region. The risks in the north are well manageable due to good documentation, area-wide monitoring and the large distance to the surface. The RAG Foundation, which has sufficient reserves, active and passive income for this purpose, takes care of the

occurrence) (qualitative or quantitative)	handling of the perpetuity tasks. The eternity tasks are divided into three areas: the treatment of mine water in the former underground mining operations, the pumping of surface water and the cleaning and monitoring of groundwater in the area of some former mining operations, in particular coking plants. In the south, the risk situation is somewhat higher. Due to centuries of shallow mining, which is often poorly documented or not documented at all, there is above all a high probability of daytime fractures. On average, there is one event per week here, but mostly in undeveloped areas. The mining companies and the local mining authorities are working intensively to document and secure the affected areas.
Criteria of intensity (qualitative or quantitative)	Depending on the situation on the surface. The size of the sinkholes is usually only a few meters, while the subsidence affects millions of people in a huge area.
Cartographic area (illustration drawing if it's possible)	 *Cartographic representation of the north-south division of the Ruhr. In the south (red): historical, near-surface mining with hazards such as sinkholes and dewatering adits. In the north (blue): industrial scale deep mining, high levels of land subsidence and flood-prone polder areas.*
Interaction with natural or technology hazards	The different hazards act differently with external factors. They are mostly influenced by surface water, especially heavy rainfall. Due to climate change, large amounts of rainfall in a short period are becoming more frequent in Germany and can be the initiator or accelerator of post-mining hazards, for example, sinkholes, environmental water pollution, hydrological disturbances, and mining induced floods. Here the interaction is high. Subsidence, induced seismicity, combustion and overheating of mining waste have a low interaction with external hazards.

5.2.3 Actors of post-mining management in the country

The primary responsibility for addressing post-mining hazards lies with the (former) mine operators and legacy companies. Under German law, this responsibility is considered perpetual liabilities, meaning it does not expire. However, when companies undergo changes such as sale, merger, or division over time, ownership and responsibility can become significantly unclear. It is not uncommon for old mining sites' responsibilities to be transferred to foreign corporations during takeovers, leaving them either uninformed or unaware of their associated obligations. If no responsible party can be identified, the respective mining authority of the country assumes the responsibility for these ongoing tasks as a substitute. In order to provide assistance and contacts for all those involved, the Research Center of Post-Mining founded the Post-Mining Competence Network a few years ago. In the meantime, 21 partners from companies, associations, authorities and research institutions are registered in this loose network: https://kompetenznetzwerk-nachbergbau.de/

This list shows an overview of the responsible mining ministries and authorities in Germany:

- Baden-Württemberg
  - Ministerium für Wirtschaft, Verkehr, Landwirtschaft und Weinbau Rheinland-Pfalz
  - Landesamt für Geologie und Bergbau Rheinland-Pfalz
- Bavaria (Bayern)
  - Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie
- Berlin
  - Senatsverwaltung für Wirtschaft, Energie und Betriebe
  - Landesamt für Bergbau, Geologie und Rohstoffe Brandenburg[1]
- Brandenburg
  - Ministerium für Wirtschaft, Arbeit und Energie des Landes Brandenburg
  - Landesamt für Bergbau, Geologie und Rohstoffe Brandenburg
- Bremen
  - Senatorin für Wirtschaft, Arbeit und Europa
  - Landesamt für Bergbau, Energie und Geologie Niedersachsen[1]
- Hamburg
  - Freie und Hansestadt Hamburg Behörde für Wirtschaft und Innovation
  - Landesamt für Bergbau, Energie und Geologie Niedersachsen[1]
- Hesse (Hessen)
  - Hessisches Ministerium für Umwelt, Klimaschutz, Landwirtschaft und Verbraucherschutz
  - Regierungspräsidium Darmstadt Abt. Arbeitsschutz und Umwelt Wiesbaden
- Mecklenburg-Vorpommern
  - Ministerium für Energie, Infrastruktur und Digitalisierung
  - Bergamt Stralsund
- Lower Saxony (Niedersachsen)
  - Niedersächsisches Ministerium für Wirtschaft, Arbeit, Verkehr und Digitalisierung
  - Landesamt für Bergbau, Energie und Geologie
- North Rhine-Westphalia (Nordrhein-Westfalen)
  - Ministerium für Wirtschaft, Innovation, Digitalisierung und Energie des Landes Nordrhein-Westfalen
  - Bezirksregierung Arnsberg Abt. 6 - Bergbau und Energie in NRW

[1] The task of the state mining authority is assumed by another federal state.

- Rhineland-Palatinate (Rheinland-Pfalz)
  - Ministerium für Wirtschaft, Verkehr, Landwirtschaft und Weinbau Rheinland-Pfalz
  - Landesamt für Geologie und Bergbau Rheinland-Pfalz
- Saarland
  - Ministerium für Wirtschaft, Arbeit, Energie und Verkehr des Saarlandes
  - Oberbergamt des Saarlandes
- Saxony (Sachsen)
  - Sächsisches Staatsministerium für Wirtschaft, Arbeit und Verkehr
  - Sächsisches Oberbergamt
- Saxony-Anhalt (Sachsen-Anhalt)
  - Ministerium für Wirtschaft, Wissenschaft und Digitalisierung des Landes Sachsen-Anhalt
  - Landesamt für Geologie und Bergwesen Sachsen-Anhalt
- Schleswig-Holstein
  - Ministerium für Energiewende, Landwirtschaft Umwelt und ländliche Räume des Landes Schleswig-Holstein
  - Landesamt für Bergbau, Energie und Geologie Niedersachsen1
- Thuringia (Thüringen)
  - Thüringer Ministerium für Umwelt, Energie und Naturschutz
  - Thüringer Landesamt für Umwelt, Bergbau und Naturschutz

5.2.4 Philosophy / actions: Mine closure

Risks are systematically identified and assessed throughout the entire mining life cycle. Anticipating risks that extend beyond the active mining period, proactive measures are taken to address them well in advance of production cessation. By law, mining operators are obligated to allocate provisions for the post-mining phase, ensuring adequate resources are set aside for potential challenges, repairs and financial compensation.

To undertake land use planning on previously used mining grounds and initiate a reclamation process in Germany, the primary law to consider is the Federal Mining Act (BBergG). This law outlines the mine closure plan, which includes measures to prevent damage to the surrounding area resulting from the decommissioned mine and associated structures and activities. The mine closure plan also covers the reclamation of the surface. However, the BBergG serves more as a process framework for the establishment, execution, and closure of mining activities. Multiple legislations must be considered when assessing and approving mine operation or closure plans, such as soil protection law, environmental and nature protection law, waste management law, water law, and occupational health and safety.

The ultimate goal of a mine closure plan is to release mining supervision by the responsible mining authority by achieving a sufficient state of reclamation. Competent authorities participate in the procedure to enforce specialized issues such as those listed above. Municipal affairs are also impacted since the municipality acts as the responsible planning authority and shapes future land use. Clarifying the land use perspective with local authorities can help access the necessary reclamation measurements early on.

It should be noted that in Germany, a federal republic with 16 states, legislative authority could be on both federal and state levels. For some types of competence, there is exclusive jurisdiction, for which only the federal government or a state government can enact a law on a specific topic. The Federal Mining Act falls under this category. Other issues, such as spatial planning and land law, fall under competing jurisdiction, where both federal and state governments are authorized to pass laws within the same legal sphere. Therefore, there are various regulations on specific issues such as distance regulations for wind energy plants. In the case of colliding norms, the federal one is favored by the judicial branch.

The mining-related legislation in Germany is primarily governed by the Federal Mining Act (Bundesberggesetz) at the federal level. In the post-mining sector, it is supplemented by various other environmental and construction laws. However, the responsibility for overseeing these laws lies with the state ministries. Depending on the size and number of mining companies in a particular state, the direct implementation and monitoring may be delegated to a subordinate authority.

5.2.5 Standards and guidelines

In Germany, a robust set of standards and guidelines exists to manage risks associated with abandoned mining sites. These regulations form a comprehensive framework that ensures the responsible and sustainable management of these sites, protecting the environment and safeguarding public health. The following German standards and guidelines are of particular importance:

- Mining Act (Bundesberg-Gesetz): The Mining Act serves as the foundational legal framework for mining activities in Germany. It includes provisions that specifically address the management and remediation of abandoned mines. By enforcing regulations related to mine closures, reclamation, and rehabilitation, the Mining Act ensures the proper handling of risks associated with abandoned mining sites.
- Federal Soil Protection Act (Bundes-Bodenschutzgesetz): The Federal Soil Protection Act establishes legal requirements for the protection of soil and groundwater in Germany. This act is instrumental in managing risks related to contaminated sites, including abandoned mines. It outlines measures and procedures for the remediation and restoration of these sites, minimizing the potential adverse effects on soil and groundwater quality.
- Technical Rules for Hazardous Substances (Technische Regeln für Gefahrstoffe, TRGS): The Technical Rules for Hazardous Substances provide detailed technical guidance on the safe handling, storage, and disposal of hazardous substances. Abandoned mines often contain hazardous substances that can pose risks to human health and the environment. The TRGS guidelines ensure that proper protocols are followed when dealing with these substances, minimizing potential hazards during site remediation and management.
- Guidelines for the Management of Mining Wastes (Leitfaden zur Bewirtschaftung von Bergbauabfällen). These guidelines specifically focus on the proper management of mining wastes, including those generated by abandoned mines. They outline best practices for waste characterization, storage, transport, and disposal, ensuring that these activities are conducted in an environmentally responsible manner. The guidelines help minimize the long-term impact of mining waste on ecosystems and human populations.
- Guidelines for the Management of Water in Mining Areas (Leitfaden zur Wasserbewirtschaftung in Bergbaufolgelandschaften). Water management is a critical aspect of abandoned mining sites, as they often present challenges related to water pollution and hydrological changes. These guidelines provide guidance on the management of water in areas affected by mining activities, including abandoned mines. They address issues such as water quality monitoring, drainage, and remediation strategies, ensuring that water resources are protected and managed effectively.
- Federal Environment Agency (Umweltbundesamt) Guidelines: The Federal Environment Agency plays a crucial role in environmental protection and provides guidelines specific to managing risks associated with abandoned mines in Germany.
- These guidelines offer practical recommendations and strategies for the identification, assessment, and mitigation of risks at these sites. By following these guidelines, government agencies, mining companies, and other stakeholders can effectively address environmental challenges and ensure the safety of surrounding communities.

Overall, these German standards and guidelines create a comprehensive and robust framework for managing risks related to abandoned mining sites. They provide clear instructions and procedures for various aspects of site remediation, waste management, water protection, and overall risk mitigation. By adhering to these regulations, stakeholders can promote sustainable practices, minimize environmental impacts, and protect public health in the context of abandoned mining sites in Germany.

5.2.6 Social aspects, transition and reactivation

Alongside the geotechnical and environmental considerations in risk management, Germany also addresses the social aspects and challenges related to transition and reactivation. The country has established a dedicated research branch within the Research Center of Post-Mining to focus on these areas. A notable example of this commitment can be seen in the upcoming coal phase-out:
The "Joint Agreement on the Future of the Coal Mining Regions" ("Gemeinsame Vereinbarung zur Gestaltung der Zukunft der Kohleregionen") is a document signed by the German federal government and the governments of the German states of North Rhine-Westphalia, Brandenburg, Saxony and Saxony-Anhalt in January 2019. The agreement outlines a plan for the phasing out of coal mining in Germany and the transformation of the affected regions towards more sustainable and diversified economic structures.
The agreement includes provisions for the shutdown of all coal-fired power plants in Germany by 2038 at the latest, as well as financial support for the affected regions to invest in infrastructure, education, research and development, and other economic activities. The total funding for the structural transformation of the regions is estimated to be around €40 billion.
The aim of the agreement is to ensure a socially just and economically viable transition away from coal mining and towards a more sustainable future for the affected regions and their communities. It is seen as a key step in Germany's efforts to meet its climate targets under the Paris Agreement.

5.2.7 Multi-hazards approach?

There are some multi-monitoring and multi-hazard approaches, depending on the companies involved, the mining hazards and the area affected. Because none of them are completely public or even used as best-practices yet, such concepts are also being developed at the Research Center of Post-Mining, TUBAF and other universities.

Guidelines and standards for assessing multi-hazards in abandoned mines typically take into consideration both the individual hazards and their potential interactions. While the specific approach may vary depending on the guideline or standard, the overall goal is to comprehensively evaluate the risks associated with abandoned mines.
In many cases, guidelines and standards acknowledge that hazards in abandoned mines can interact and create compounded risks. For example, the presence of unstable ground conditions may interact with environmental hazards such as water contamination, leading to an increased risk of subsidence or the release of harmful substances. Similarly, the release of hazardous gases may pose risks to both human health and the stability of the mine structure. These interactions between hazards can significantly impact the overall risk profile of an abandoned mine.

To assess multi-hazards in abandoned mines, guidelines and standards often adopt an integrated approach. This involves considering the potential interactions between different hazards and evaluating their combined effects. It may involve conducting risk assessments that examine various scenarios, considering how the hazards can influence each other and contribute to overall risks.
Additionally, these guidelines and standards may provide specific methodologies, tools, or frameworks to assess and manage multi-hazards. They may recommend conducting site investigations, analyzing historical data, monitoring key parameters, and utilizing modeling techniques to better understand the complex interactions between hazards.

The objective is to ensure that a holistic evaluation of multi-hazards is carried out, considering both the individual risks and their potential combined effects. This approach allows for a more comprehensive understanding of the risks associated with abandoned mines and facilitates the development of effective risk management strategies.
The International Council on Mining and Metals (ICMM), the International Organization for Standardization (ISO), and the United Nations Framework Convention on Climate Change (UNFCCC) provide more specific and authoritative information on the assessment of multi-hazards in abandoned mines, considering the interactions between different hazards.

5.3 Greek experience

In Greece the following hazards are considered as the main post-mining hazards:

1. Ground movement:
   1.1. Subsidence (underground) and Settlement (underground and on the dumping areas),
   1.2. Slope movement (Open pit mines and dumps),
   1.3. Induced seismicity,
   1.4. Crevice (In surface mines, behind the slope crest and other excavation sites. In underground mines, on the surface). It is noted that in Greece, seismicity is considered a triggering factor to examine potential hazards, like slope stability. Potential hazards are examined in all mines.
2. Environmental pollution:
   2.1. Environmental water pollution (surface/pit lake/underground),
   2.2. Environmental pollution from spoils (surface/underground).
3. Hydrological issues: Hydrological disturbances, mining-induced flood (pit lake, surface, underground)
4. Gas/fire: a) Gas emissions linked to mining (underground) and b) Combustion and overheating of mining waste (waste embankment).

5.3.1 Methodology of hazards assessment:

A systematic network is applied for the continuous monitoring, recording, and assessment of probable hazards that may occur. The aim is to identify probable hazards, take immediately the appropriate remedial measures, PPC improve the procedures followed, and minimize potential risks. The priority of PPC is to increase the levels for safe operation and, at the same time, comply with the legislation.

Regarding the monitoring process, the received data are continuously elaborated: maps and diagrams are produced to evaluate the spatiotemporal development of a specific hazard, and permissible limits are checked. Permissible limits are considered for each environmental hazard to comply with the environmental legislation, and warning levels are considered for each geotechnical hazard to take appropriate proactive and reactive activities and measures. It is essential to note that the data received via the monitoring program are evaluated also considering the hydrogeological environment, the construction or/and operational phase of the project, and the experience of the engineers in similar cases.

Mines in Greece have dense monitoring networks detecting air quality, ground movements, and groundwater tables. A tool to assess hazards is formed by integrating and analyzing these data. The synergistic utilization of the remote sensing field, laboratory, historical data, and literature enables the creation of a database. This database encompasses topographic, hydrogeological information, land uses, and geotechnical information, which in turn enable the identification of the hazards' impacts.

Geotechnical hazards methodology

In PPC lignite mines, the geotechnical department is responsible for the safe continuous operation of the mines and can prevent loss of life, equipment, production, and possibly the loss of the mine. The scope of the department is divided into three different categories:

a) Design Studies (Geotechnical, geological, slope stability analyses, etc.),

b) Monitoring, and

c) Immediate actions in case of instability.

Technical studies are conducted before the start and throughout the excavation works, and analytical and numerical methods are applied for slope stability analyses. Design calculations are based on on-site recordings, and geological mapping and back analyses are performed to improve stability conditions and to continuously ensure the safety of the pit slopes.
Several methods for monitoring the ground deformation at the surface lignite mines have been developed. Most of the measuring techniques include GPS, high accuracy Total Stations, borehole inclinometers, structure tilt-meters, borehole settlement meters, satellite InSAR, aerial photography, and most importantly, continuous experienced eye observation. Also, data collection can usually be automated and/or doesn't require highly skilled staff. Slope monitoring is usually performed by geodetic measurement of rates of movement in three dimensions (in mm/day) using a set of reflector targets on the slope and high-precision geodetic instruments (total stations) placed in stable positions across the slope.
The lignite mines in Western Macedonia and Megalopolis are being constantly monitored, where mine planning, mine size, time constraints, the expected magnitude of movement, terrain morphology, and geology dictate the monitoring scheme. A monitoring system (Minefeed) has been developed to evaluate measurements. Minefeed is a database that allows the immediate uploading of all micro-movement topographic measurements that are collected by PPC (with different methods and instruments). Measurements are calculated automatically to produce the diagrams in real-time. Also, many PPC executives have access to the results of the measurements through a web browser.

The monitoring process normally constitutes three steps:

- The first one is to establish the objectives, needs, and advantages;
- The second step includes the actual measurement and recording of field data. Issues to be dealt with, which will have been thoroughly considered during the design of the monitoring system, are measuring techniques and frequencies, accuracy, precision, and personnel responsibilities;
- The third step is the interpretation and reporting of monitoring data. This involves processing, analysis, interpretation, and presentation of monitoring data. The reporting of results and documenting of events, decisions, design changes, and cost-benefit analysis complete the monitoring process.

Environmental – hydrological hazard methodology
Particular emphasis on the systematic monitoring of various environmental parameters is given to comply with the environmental legislation, aiming to minimize and address any environmental impact. The monitoring of the mine water refers to the monitoring of water quality (surface and groundwater) and monitoring of the groundwater table:

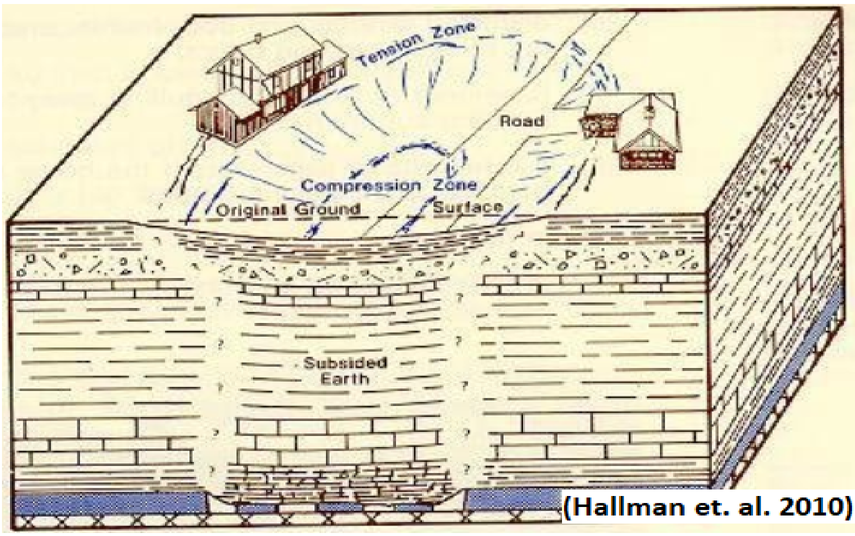
- Continuous monitoring of physicochemical parameters such as pH, temperature, conductivity, and pressure (operation of the automatic telemetric network to measure physicochemical data);
- Daily, monthly, bimonthly, quarterly, and semi-annual site measurements with portable instruments of physicochemical parameters such as pH, E.C., TDS, SS, KMnO4, Fetot, Mn, D.O, Total Hardness CaCO3, HCO3-, Cl-, SO4-2, NH4+, SiO2, NO3-, NO2-, Ca, Mg, Na, Fe, TDS, SS, KMnO4, K, Na, Mn, PO4-2 and trace elements and heavy metals such as Zn, Ag, Cr, As, Cd, Hg, Cu, Ni, V, Mo, Pb, B, Se in selective mining sumps, dewatering wells, and drinking sites;
- Quarterly measurements of various chemical parameters such as SiO2, Ca, Mg, Na, K, P2O5, and heavy metals Pb, Ni, Cd, Hg, Zn, Cr, V, Cu, As, B, Se in river water;
- Continuous monitoring of water level in selective mining sumps (surface water) via the operation of an automatic telemetric network. The continuous monitoring of the inflows of water in the sumps is necessary for the maintenance of the sump level within the desired safety limits to ensure safety in the mine's operations. The same applies to pit lakes, where

post-mining end-uses are also considered, such as hybrid power plant facilities, photovoltaic parks, etc;

- Continuous monitoring of water level in pumping wells (groundwater) via the operation of an automatic telemetric network and site measurements with portable instruments. The aim is to monitor the groundwater level fluctuation and evaluate the mine activities' impact.

Examples of hazard assessment:

Table 6. Example of hazard assessment – Greece

Name of hazard	Subsidence/Landslides
Type of mine	Underground mine (Aliveri mine, in Evia island, Greece)
Phenomenon description	After the completion of mining operations, cracks, voids, and gaps have formed new flow patterns. The aquifers have been connected in some areas, and seawater – which initially was isolated by a clay layer – had inrushed into the underground works. The voids created by the underground mining activities caused extended faults, reaching even the ground surface and thus, causing the underground collapse. Additionally, the pit lake area formed at the final voids of the surface mines, which seems an aesthetically acceptable solution. However, due to the subsidence at the north slope, this area is not accessible, and the pit lake is not stable and functional. References: Dimitrakopoulos, D.; Koumantakis, I.; Vasileiou, E. Water management after the closure of underground lignite mine in Aliveri, Greece. SGEM, 2009 Vasileiou, E.; Stathopoulos, N.; Stefouli, M.; Charou, E.; Perrakis, A. Evaluating the Environmental Impacts after the Closure of Mining Activities Using Remote Sensing Methods-the Case Study of Aliveri Mine Area. IMWAQ, 2012 MINWATER- ECSC Research, Consequences of closures of mines in water circulations, 2001.
Illustration drawing	
Criteria of predisposition (Probability of	The hazard depends on the following factors:

occurrence) (qualitative or quantitative)	1) The erosive water activity. The surface water, entering the high permeable conglomerate and breccia, takes away their clay-sand connective material and results in the augmentation of the voids. 2) The residual voids in combination with erosion. The voids created due to the underground mining have caused extended faults reaching even the ground surface, causing the underground collapse. The underground voids have been filled up with water, which caused the strength degradation of the formations and the pillar destruction, which, subsequently, ends in the collapse of the galleries and, indirectly, in the subsidence phenomenon.
Criteria of intensity (qualitative or quantitative)	Hydraulic conditions: The presence of water in post-mining areas can significantly influence the intensity of mine subsidence due to the erosive power of water. Moreover, water increases the weight and pressure on the surface, potentially accelerating the subsidence phenomenon. Land Use: Land use and surface load distribution play a critical role in the susceptibility assessment to mine subsidence (for instance, a concentrated load of industrial facilities). Climate Conditions: Extreme weather events, such as heavy rainfall, can further exacerbate subsidence.
Cartographic area	 void on the surface, North of the main subsidence area, PPC source
Interaction with natural or technology hazards	In general, subsidence can potentially trigger /influence other hazards such as settlement (high), slope movement (high), rock falls (high), crevice (high), water pollution (medium), water disturbance underground (medium), and gas emissions (high). And subsidence is triggered/ influenced by: seismicity (high), water disturbance (high), crevice (medium), and settlement (medium).

5.3.2 Actors of post-mining management in the country:

The Legislation applied in Greece concerning activities in mining areas is described in detail hereinafter.

5.3.3 Philosophy/actions of risk management:

The Legislation governing the mining and minerals industry in Greece, that covers the regulations regarding exploitation works and addresses environmental and health & safety issues is the “Regulation on Mining and Quarrying Activities” (KMLE) (Ministerial Decision 12050/2223/2011, Gov. Gaz. B'1227). Specifically, the KMLE is a set of rules that apply to all types of mining and quarrying sites during the activities of exploration, extraction, exploitation, or treatment of mineral raw materials, as well as during rehabilitation. It defines the criteria that should be considered to achieve rational operation, defines the obligations for mine operators, and sets the overall framework for the study, organization, operation, supervision, and inspection of all works. Also, it regulates health and safety issues for the working staff and the citizens of the surrounding areas and sets terms and measures for the protection of the environment, cultural heritage, infrastructure, etc. Furthermore, it envisages the documents required to control the compliance of the quarry/mine operators with the provisions of the KMLE.

Also, Law 4014/2011 on Environmental licensing of projects and activities provides for the environmental assessment of works and activities to grant authorization (environmental permitting - AEPO). The Law applies to the permitting of mining projects and activities in combination with Joint Ministerial Decision 167563/2013 (Gov. Gaz. B’964), as amended by the Joint Ministerial Decision 1915/2018 (Gov. Gaz. B’304), which specifies the procedures and criteria for the environmental licensing procedure. In the context of environmental licensing for relevant facilities, Environmental Impact Studies (EIS) are prepared and submitted to the competent licensing authority from time to time which, among other things, describe the operation of the activity, raw materials, other materials, waste generated, etc. The EIS also examines possible environmental impacts and measures to address them based on the provisions of the environmental legislation in force.

The main first-instance competent authorities responsible for issuing permits and licenses relevant to the mining sector are, at the national level, the Ministry of Environment and Energy (YPEN) and, at regional/local level, the 7 Decentralised Administrations and the 13 Administrative Regions (regional authorities) respectively. The Ministry (YPEN) is the competent authority for the approval of technical exploitation studies as per KMLE and the evaluation of each required Environmental Impact Study (EIS), which leads to Environmental Permission (AEPO). The Greek Mining Legislation is framed by extensive environmental legislation, the implementation of which is always a pre-requisite for the final permitting of all mining projects and activities (Approval of Technical or Feasibility Study and Approval of Environmental Terms).

The applicable legal provisions have been adopted to recent European legislation related to environmental and health & safety issues for the extractive industries, including the EU Environmental Impact Assessment (EIA) Directives 85/337/EC and 97/11/EC, the Habitats Directive 92/43/EC, the Water Framework Directive (WFD) 2000/60/EC, the EU Extractive Waste Directive 2006/21/EC, etc. More specifically, protecting the NATURA network, Archaeological Sites, Water Resources, Forest Areas, and Landscape. It is highlighted that within the Environmental Permitting of a mining project, all potential conflicts arising should be examined while the competent authorities dictate measures that prevent or mitigate potential adverse impacts.

The holistic approach to operation and management in mining and post-mining areas is of great importance, as nowadays, mines in Greece must comply with very strict legislation and include, inter alia, the proper and efficient management of water resources. The implementation of the Water Framework and Floods Directives (European Commission, Directorate-General for Environment 2021) is obligatory for sustainable ground and surface water management. The mines must consider many aspects of water management and identify all actions and measures to be taken within the river basin district to deliver the objectives of Water Framework and Floods Directives, including their “daughters”, as these are described in National River Basin Management Plans (Gov. Gaz. 4676/B/29.12.2017 2017; Gov. Gaz. 2689/B/6.07.2018 2018).

Currently, Special Spatial Plans (SSP) are being developed, in the context of the Just Transition Development Plan of lignite areas, in the post-mining era.

5.3.4 Multi-hazards approach

No hazard interactions approach exists in Greece for the Mining and Post Mining areas.

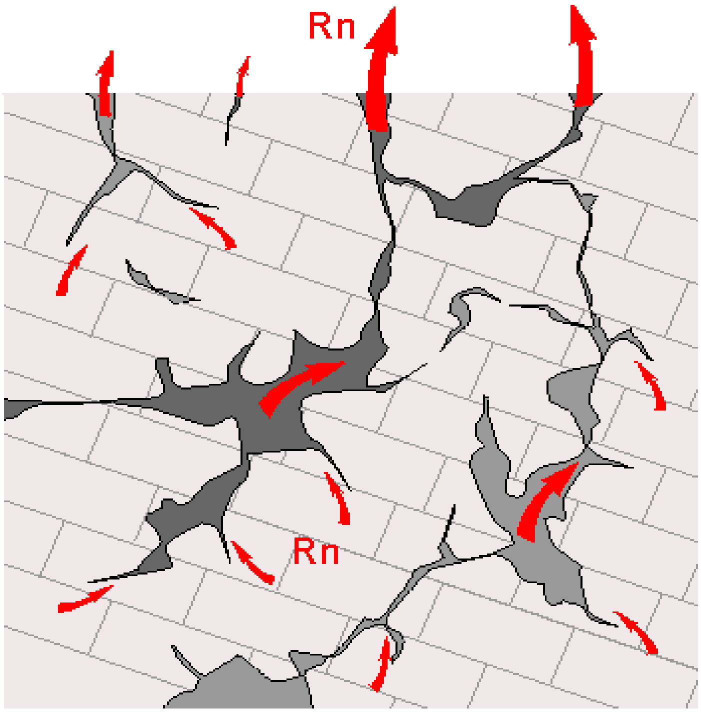
5.4 Polish experience

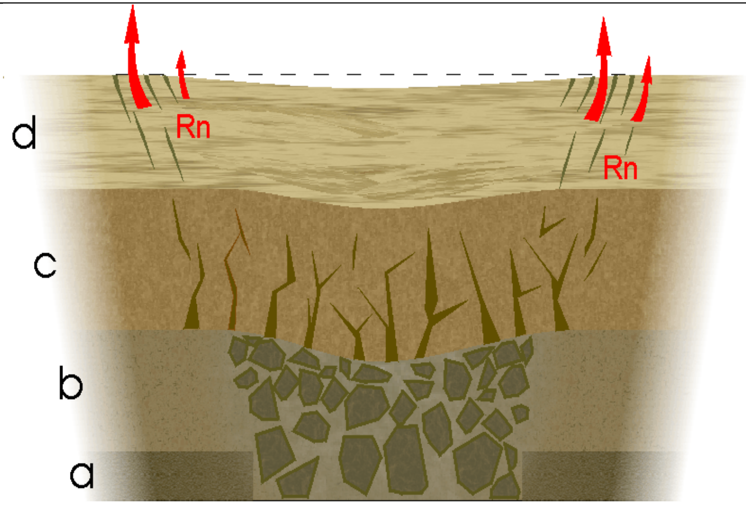
In Poland the following hazards are considered for the post-mining hazards:

1. Ground movement
2. Gas emissions
3. **Radiation**
4. **Seismicity**
5. Hydrological disturbances
6. Combustion and self-ignition

5.4.1 Example of hazard's assessment

Table 7. Example of hazard assessment – Poland

Name of hazard	**Ionizing radiation emissions**
Type of mine	Underground coal mine
Phenomenon description	The release of high-energy radiation (ionizing radiation) during coal mining. In post mining areas, the source of ionization emissions is radon, radioactive noble gas. Radon (and radium, the parent nuclide) is the member of uranium decay chain which is present in all types of rocks.
Illustration drawing	 Fissures and cracks enabling radon migration (e.g. Triassic dolomites or limestones)

<table>
<tr><td></td><td>

Pathways of radon migration over extracted coal bed. The radiation propagates through the different layers: a: mining layer, b: goaf layer, c: continuous including cracks, d: subsurface layer.</td></tr>
<tr><td>Criteria of predisposition (Probability of occurrence) (qualitative or quantitative)</td><td>This hazard depends on:
- physical parameters of rocks and soils (presence of fissures and cracks);
- disintegration of rock body caused by mining activities (past and temporary),
- opened pathways for gases in rock,
- co-migration of methane, CO_2 and radon,
- permeability of subsurface layers and soils.
Meteorological conditions such as precipitation intensity, occurrence of snow cover, periods of drought may reduce or facilitate the migration of radon.
Enhanced radon concentrations in soil gas and in dwellings are measured in sites in areas heavily transformed by coal mining, over mining voids, in the vicinity of shafts, shallow mine workings, etc.</td></tr>
<tr><td>Criteria of intensity (qualitative or quantitative)</td><td>For radon concentrations in dwellings recommended value is 300 Bq/m³ (Atomic law, Prawo atomowe Dz. U. z 2023 r. Poz. 595). For building sites the uniform method can be applied for assessing the risk of radon penetrating from the underlying soil or bedrock, based on determining the radon index of the building site, proposed by Czech scientists.
Czech method of assessing radon risk of building sites
<table>
<tr><th>Risk category</th><th colspan="3">Radon concentration in soil, C_{Rn} (kBq/m³)</th></tr>
<tr><td>Low</td><td>$C_{Rn} < 30$</td><td>$C_{Rn} < 20$</td><td>$C_{Rn} < 10$</td></tr>
<tr><td>Medium</td><td>$30 \leq C_{Rn} < 100$</td><td>$30 \leq C_{Rn} < 70$</td><td>$10 \leq C_{Rn} < 30$</td></tr>
<tr><td>High</td><td>$C_{Rn} \geq 100$</td><td>$C_{Rn} \geq 70$</td><td>$C_{Rn} \geq 30$</td></tr>
<tr><td></td><td>Low permeability</td><td>Medium permeability</td><td>High permeability</td></tr>
</table>
Neznal M. et al. (2004): The new method for assessing the radon risk of building sites - Czech. Geol. Survey Special Papers, 47. p., CGS Prague.</td></tr>
<tr><td>Cartographic area</td><td>In Upper Sielesian Coal Basin, the areas of “radon prone areas” to some extent overlap sites of outcrops of Triassic dolomites and limestones and areas where historical shallow exploitation was performed – see Fig. 3 below.</td></tr>
</table>

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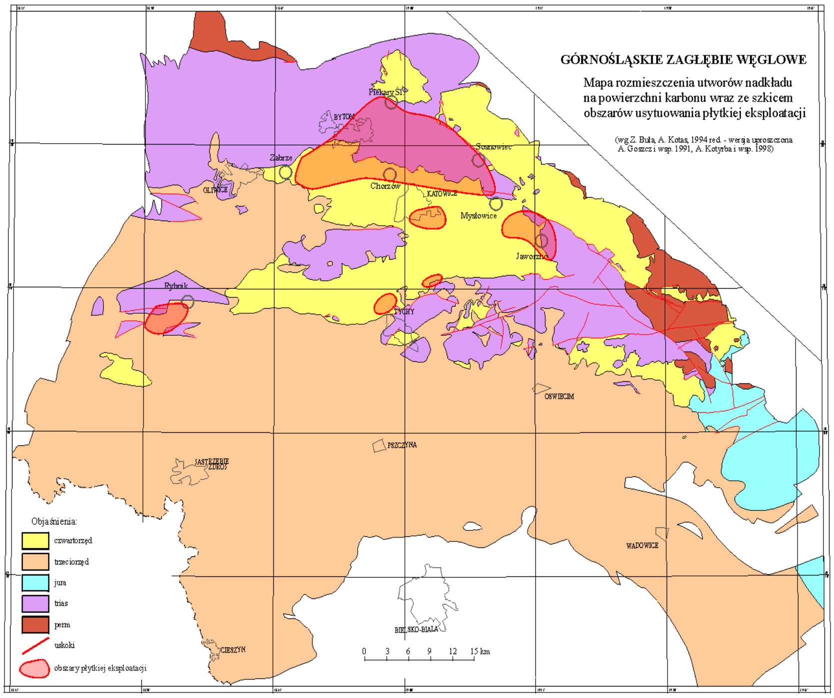
<td></td>
<td>

The map of the overburden geological formations on the Carboniferous (based on Buła & Kotas, 1994) - purple – Triassic formations. Sites marked in pink – areas of shallow exploitation</td>
</tr>
<tr>
<td>Interaction with natural or technology hazards</td>
<td>The most expected/likely interactions: subsidence (medium), flooding (medium), combustion (low), crevice (high), seismicity (induced: high), local collapse (high), natural sinkhole (medium)</td>
</tr>
</table>

5.4.2 The main actors

For radon hazard, actors of post-mining management in the country are:Minister of Health, General Sanitary Inspectorate, Provincial and District Sanitary and Epidemiological Stations.

5.4.3 Philosophy / actions:

- In case of radon in dwellings

Recommendations of Polish Radon Center – Scientific Network, related to radon measurements in dwellings – chart below (Figure 15):

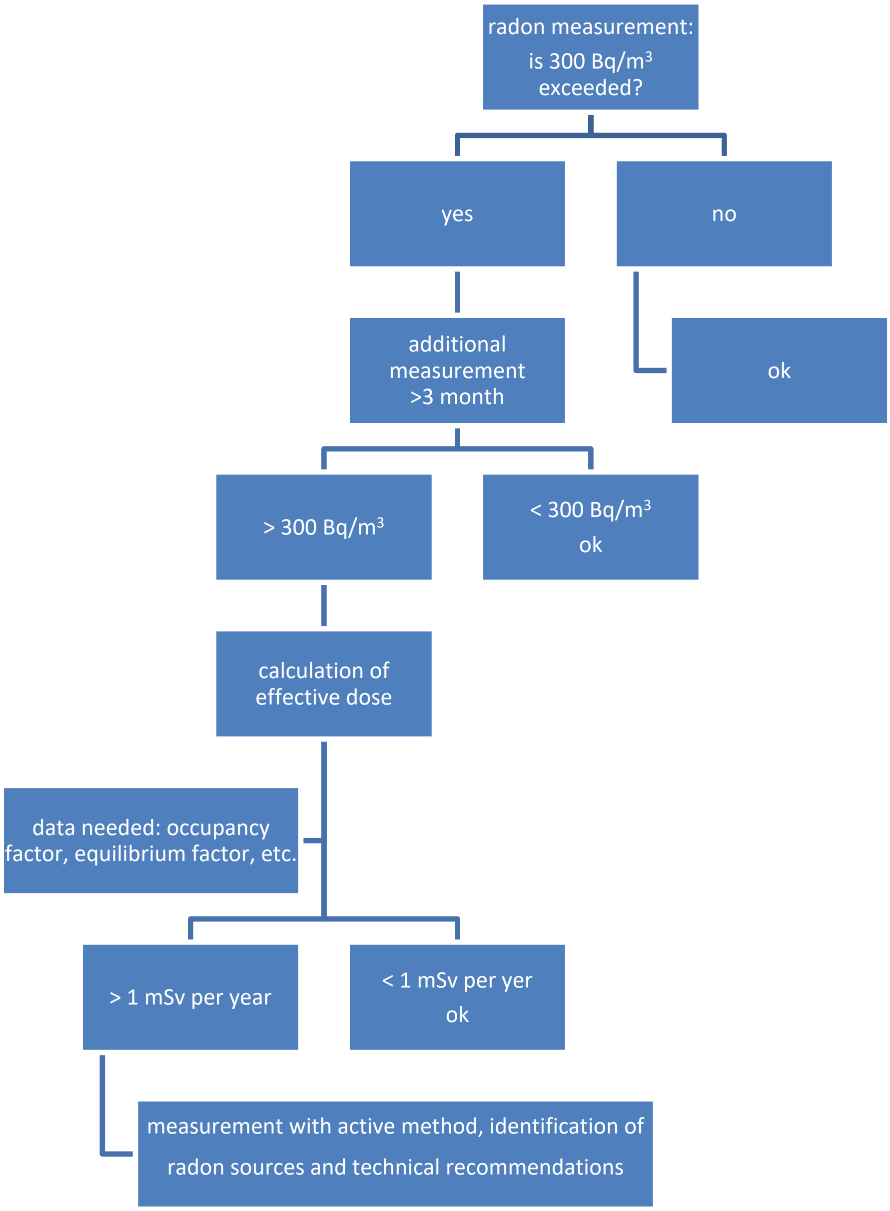


Figure 15. Recommendations of Polish Radon Center

5.4.4 General methodology information:

There are no regulations in Poland that would require the performance of risk assessments and analyzes in connection with the closure of mines. The basic legal act defining the rules and conditions for undertaking, performing and terminating activities in the field of mining operations, including hard coal, in Poland is the Geological and *Mining Law Act of June 9, 2011 (i.e. Journal of Laws of 2011, no. 163, item 981, with changes).* The Act also defines the requirements for the protection of mineral deposits, groundwaters and other elements of the environment in connection with the above activities, as well as the rules for exercising supervision and control over these activities. Pursuant to the *Act on the functioning of hard coal mining (Journal of Laws of 2022, item 1309)*, the scope of mine liquidation is defined by the mining company in the operation plan of the liquidated mining plant. In this document, apart from information on the method and schedule of decommissioning of the mining infrastructure, the following should be indicated:

- predicted development of hazards and methods of removing threats during liquidation,

- water hazard and hydrogeological conditions, including the impact of changes in hydrogeological conditions related to closure on neighboring mines, underground and surface waters, water intakes used to supply the population, planned method of monitoring during and after closure,
- risk of radioactive substances: predicted development of the threat of radioactive substances,
- impact of the mine liquidation on the environment and the facilities and equipment located on the surface,
- determination of the category of suitability of the area after the end of mining activities and plans to limit and remove the negative impacts of the activity.

The legislator does not impose on the entrepreneur the method of assessing possible risks related to the liquidation of a mining plant.
For areas subject to anthropopressure, including mining and post-mining areas, only guidelines or instructions for assessing certain threats have been developed, including:

- maps of degraded areas,
- documenting geological and engineering conditions in the areas of liquidated mines,
- threats from mining excavations connected to the surface, located in the areas of liquidated underground mining plants,
- risk assessment for groundwater intakes.

For the assessment of hydrological and hydrogeological threads and disturbances, certain pathways of analyses are recommended. For example, the Ministry of the Environment and the National Fund for Environmental Protection and Water Management have developed an *Instruction for the development of a map of degraded areas with increased natural risk*, in which they recommend the use of the method of assessing the groundwater vulnerability to pollution (DRASTIC) in the analysis of groundwater threats in anthropogenic areas. In this method, the vulnerability index (IPZ) is determined according to the formula:

$$\mathbf{IPZ = \Sigma(weight\ of\ criteria\ x\ range\ of\ parameter)}$$

Where the weight of the parameters is selected on the basis of the assumed significance of a given factor in the assessment of the sensitivity of the aquifer system to pollution. The classes of vulnerability ranges (from very low to very high) and their range in the classic method are determined by its authors (Aller., 1987) - this method accepts modification resulting from the specificity of the area. In relation to hydrogeological and hydrological disturbances, the *Act of 20 July 2017 - Water Law (Journal of Laws of 2017, item 1566, with changes)* introduced not only new regulations regarding the establishment of protection zones for water intakes, but also imposed, among others, the obligation to perform a risk analysis (RA) for groundwater and surface water intakes and submit it to the competent voids. Due to the presence of groundwater intakes also in mining and post-mining areas (liquidated mines), the owners of these intakes are obliged to carry out such a study. For this purpose, the Polish Geological Institute in Poland has developed a methodological guide entitled *Groundwater intake protection zones - risk analysis and design, part I - risk analysis for the establishment of groundwater intake protection zones.* This guide includes the possibility of using a three-parameter matrix and numerical modeling for risk analysis.

In case of lack of specific instruction/guidelines, specialists performing the assessment for all range of threats, can use the general approach.
Quantification of risks:
Mathematically, risk can be represented by the dependence of the probability of a hazard occurrence to its consequences (effects) according to the basic formula:

$$r_{ij} = P_i \times C_j \qquad (1)$$

where: **rij** is risk value for the probability i, and the loss (consequences) j, values; **Pi** is the probability of occurrence of undesirable events, i = 1, 2,…, n; **n** is the scale for the probability parameter, **Cj** is the consequences or relative losses associated with a given probability, **j** = 1, 2,..., m; and m is the scale for the losses parameter.

The likelihood can be rated as rare, up to almost certain. The scale of consequences, including financial losses, can change (for example from insignificant up to catastrophic).

The example of a simple risk matrix, structuring way of identifying impacts and range (scale) of measures and activities, that would be needed is below. The rating of risk is changing from I very high risk (the monitoring and control is needed, very expensive measures should be implemented) to V low (no changes in monitoring and control, inexpensive measures possible).

Table 8. Risk matrix based on the hazard rating (A to E) and the consequence rating (1 to 6)

Likelihood rating						
E	IV	III	II	I	I	I
D	IV	III	III	II	I	I
C	V	IV	III	II	II	I
B	V	IV	III	III	II	I
A	V	V	IV	III	II	II
	1	2	3	4	5	6
	Consequence rating					

The Ministry of the Environment also recommends the publication of a study entitled *Principles of documenting geological and engineering conditions for the purpose of mines closure.* Regarding liquidated mines (underground, opencast, boreholes), the criteria for qualifying the areas of liquidated mines for development and reclamation are indicated. Categories of mining areas were introduced due to their suitability for development, because of deformations, land flooding, sinkholes resulting from the mine flooding. For various qualification criteria (e.g. water conditions, soil conditions, mining influences, etc.), geological and engineering zoning was introduced, qualifying the areas of liquidated mines into areas suitable for development, areas conditionally suitable (after prior treatment) and areas unsuitable for development.

For the areas of liquidated mines, the State Mining Authority in Poland recommended the development of the *Methodology for assessing threats from mining excavations connected to the surface, located in the areas of liquidated underground mines.* In this study, 17 assessment criteria were indicated (including water conditions in the overburden and the water conditions in the shaft during closure), assigning ranges of point values to each of the criteria. Threats are classified on the basis of the sum of points assigned to individual criteria. 4 categories of threat to the surface from the sides of the shafts were indicated: from no threat (sum of points <10, probability 0.001-0.01), through low degree of threat (sum of points 11-20, probability 0.01-0.1) and medium degree of threat (sum of points 21-35, probability 0.1-0.5) to a high degree of threat (sum of points >35, probability 0.5-1.0).

5.4.5 How the process of assessing threats in the areas of liquidated mines is conducted in practice

It should be underlined that for some time, all mines, at the liquidation stage, have to prepare documentation in accordance with the recommendations of *Principles of documenting geological and engineering conditions for the purpose of mines closure*. All necessary analyzes and measurements are performed by external experts selected in a public tender.
The final assessment is performed in accordance with the existing guidelines, or in the absence of guidelines (in case for some hazards), based on the knowledge and experience of experts and/or general approach described above. Finally, experts classify land areas into 3 categories, due to restrictions on their use for construction purposes:

- useful area (not anthropogenically transformed);
- conditionally useful area (transformed);
- unsuitable area (heavily transformed).

The mine obligatory provides the expert opinion with full documentation to the archives of the State Mining Authority.
If a mine is transferred to the SRK S.A. (Mine Restructuring Company), the set of documents is also submitted. SRK completes mine decommissioning (if not completed). As part of the liquidation of the mine, in accordance with the recommendations presented in the documentation, SRK conducts reclamation, backfills the shafts and pumps out water from drainless basins. If all tasks related to liquidation are completed, the Minister of the Environment issues a decision to terminate the mining concession.

5.4.6 The role of Marshal Office, municipal offices and local administrations

The Voivodship Office, Marshal Office and local administrations usually apply to the State Mining Authority for access to documentation related to the liquidation of individual mines. Very important platform for cooperation between SRK, regional mining offices (branches of the State Mining Authority) and local administrations are the so-called "Communication Teams". They meet twice a year to discuss the progress of liquidation and mitigation of specific hazards (eg. subsidence, hydrological disturbances, gas emission) in selected mining areas. The meetings are attended by representatives of inhabitants(councillors) and interested entrepreneurs (for example developers).

Financial issues

- The costs of repairing damage to buildings shall be paid by the mine or are covered by SRK if the mine was transferred to the company.
- The Geological and Mining Law regulates issues related to the financing/refinancing of mining damage and/or protection against damage.
- Residents of post-mining areas can use templates of applications for reimbursement of damages, which can be found on the websites of SRK or mines.

5.4.7 Multi-hazard approach?

Up to now, there is no multi-hazard approach in Poland.

5.5 European feedback

These guidelines and standards play a crucial role by providing a comprehensive and internationally recognized framework for effectively managing the risks associated with abandoned mining sites. Widely adopted by governments, mining companies, and various stakeholders worldwide, they serve as invaluable resources in addressing the multifaceted challenges posed by these sites.

Within the scope of the POMHAZ research project, our focus revolves around investigating the existing European and major global standards and guidelines that govern the management of risks related to abandoned mining.
By delving into these prominent guidelines, we aim to gain valuable insights and contribute to the development of innovative strategies and solutions.

Among the notable standards and guidelines, the followings are identified:

1. The International Mine Water Association (IMWA) Guidelines hold a prominent position. These guidelines present a comprehensive framework for managing various aspects related to mine water, including the challenges posed by abandoned mines. By providing guidance on effective water management techniques, they contribute significantly to mitigating risks associated with abandoned mining sites.
2. Additionally, the European Mine Water Association (EMWA) Guidelines have been instrumental in managing and mitigating environmental risks linked to abandoned mines within the European context. These guidelines offer valuable insights and strategies to safeguard the environment and minimize potential hazards resulting from abandoned mining activities.
3. Recognizing the importance of proactive risk management, the International Council on Mining and Metals (ICMM) Guidelines focus on assisting mining companies in effectively addressing the environmental and social risks associated with their operations, including mine closures. By adhering to these guidelines, mining companies can implement sustainable practices and ensure responsible closure procedures, thus minimizing the long-term impact on local communities and ecosystems.
4. In the pursuit of environmental management and risk mitigation, the International Organization for Standardization (ISO) 14001 standard emerges as a critical tool. This standard specifically targets the establishment of robust environmental management systems, offering a structured approach to managing risks related to abandoned mines. By adopting ISO 14001, stakeholders can integrate environmental considerations into their operations and effectively address the challenges posed by abandoned mining sites.
5. Within the European Union, the Mining Waste Directive holds paramount importance in regulating the management of waste generated by extractive industries, including abandoned mines. This directive outlines minimum requirements that must be met to ensure proper waste management practices, thereby minimizing potential environmental and societal impacts stemming from abandoned mining operations.
6. Beyond Europe, the United States Environmental Protection Agency (EPA) has developed guidelines aimed at managing the environmental risks associated with abandoned mines. These guidelines provide valuable insights into addressing the challenges posed by abandoned mining sites, emphasizing the importance of pollution prevention, site characterization, and effective remediation strategies.
7. Moreover, the United Nations Framework Convention on Climate Change (UNFCCC) has recognized the significance of addressing risks associated with abandoned mines in its efforts to combat climate change. The UNFCCC has published guidelines specifically focused on managing these risks, underscoring the intersection between abandoned

mining sites and climate change mitigation and adaptation strategies. By incorporating these guidelines into their practices, stakeholders can contribute to global sustainability goals while effectively managing the risks posed by abandoned mining activities.

It is important to highlight that these standards can also be categorized and analyzed at local, regional, national, and international levels. However, the previously mentioned classification of analyzed risks includes also general standards as well as those focused on human, machine, and environmental aspects. The classification of the analyzed standards and directives is visually represented in Figure 16.

In addition, there are also several ISO standards and guidelines relevant to post-mining assessment. Here are some of the most important ones, along with their codes and publication dates:

- ISO 14001:2015 Environmental Management Systems - Requirements with guidance for use. This standard provides a framework for organizations to establish and maintain an effective environmental management system.
- ISO 14004:2016 Environmental Management Systems - General Guidelines on Implementation. This guideline provides additional guidance on the implementation of ISO 14001 and assists organizations in achieving their environmental objectives.
- ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework. This standard provides principles and guidelines for conducting life cycle assessments, which can be useful in assessing the environmental impacts of mining and post-mining activities.
- ISO 31010 is a standard developed by the International Organization for Standardization (ISO) that provides guidance on risk assessment techniques. It is titled "Risk Management - Risk Assessment Techniques" and was first published in 2009.
- ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines This standard provides detailed requirements and guidelines for performing a life cycle assessment, including inventory analysis, impact assessment, and interpretation of results.
- ISO 12100:2010 is a standard developed by the International Organization for Standardization (ISO) titled "Safety of machinery - General principles for design - Risk assessment and risk reduction. It is similar to ISO 138492:2012 and ISO141211:2007
- ISO 26000:2010 Guidance on social responsibility. This standard provides guidance on integrating social responsibility into an organization's policies, practices, and core activities. It can be relevant for post-mining assessments that consider social impacts and stakeholder engagement.

It's important to note that these standards and guidelines are not specific to post-mining assessment but provide valuable frameworks and tools for conducting environmental and social assessments in various industries. However, there are two working technical groups (TC) in France concerning post-mining standards: AFNOR X14A, an ISO technical group entitled “Mining Technical Committee” (ISO_TC82 Mining). The second group concerns the Managing mining legacies - Requirements and recommendations. Ineris participates effectively to the two groups for improving the European norms in term post-mining management.

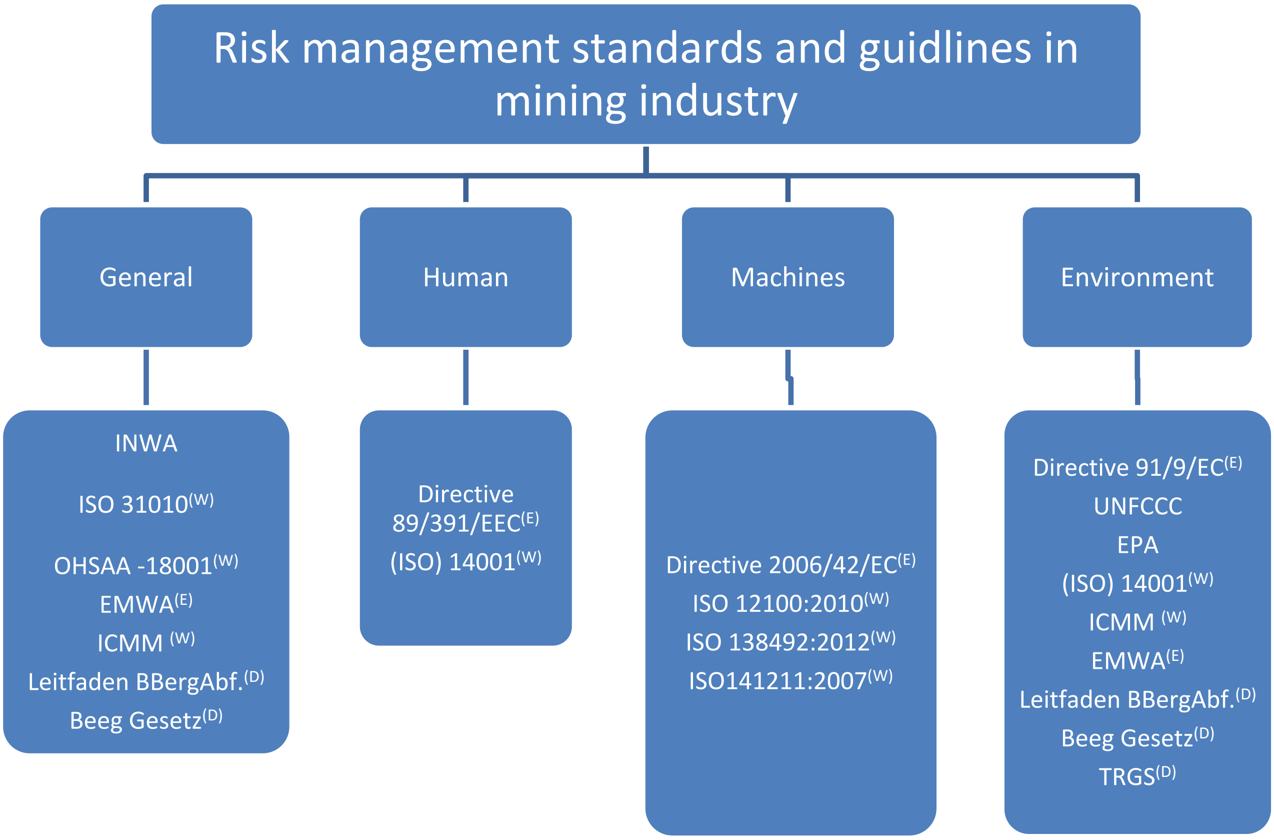


Figure 16. Classification of the main risk-related standards for the mining sector (where: (W)-global standards, (E)- standards applicable in Europe, and (D) standards applicable in Germany)

In conclusion, these guidelines and standards serve as invaluable resources for managing risks related to abandoned mining sites. By adopting and implementing these frameworks, governments, mining companies, and stakeholders worldwide can ensure the responsible and sustainable management of these sites, mitigating potential hazards and safeguarding the environment and surrounding communities for future generations.

5.6 Synthes and critical analysis

This section presents a synthesis and a critical analysis of the post-mining hazards or categories of hazards. Table 9 listed 6 groups of hazards related to mining activities (H1 to H6). Germany and Greece recognise 4 groups, Poland and the France recognises 4, that is the maximum including the radiation and pollution. The very important feedback from this study is that we have not at the European scale the same number of hazards related to coal mines. The table also tries to rank the hazards according to the number of events and reclamation, in the different countries. That means H1 is more frequently observed than H2. Thus, it seems that the ground movement (sinkhole) is the first one. Several sinkholes occur per year and causes relatively important damages. They are associated to other hazards such as flooding. The feedback from the different European countries regarding the post-mining hazards and associated risks, highlighted that:
Firstly, the number of the hazards varies from one country to another. The ground movement, pollution, combustion, and gas are common for the four countries. However, in Poland, two

additional hazards are listed: radiation and seismicity (induced seismicity). We have noticed also that self-heating is associated to the fire for Germany and Greece.

The classification differs from one country to another. This classification is not definitive and need additional information and data to confirm the tendency.

Table 9. Main categories of post-mining hazards and

Mining hazard	H1	H2	H3	H4	H5	H6
France	Ground Movement	Combustion	Flooding	Gas	Radiation	Env. Pollution
Germany	Ground movement	Env. Pollution	Hydrological issues	Gas – fire		
Greece	Ground movement	Env. Pollution	Hydrological issues	Gas – fire		
Poland	Ground movement	Gas	Radiation	Seismicity	Hydrological disturbances	Combustion and self-ignition

Secondly, the methods and tools used to assess the post-mining hazards varies from one country to another. For instance, in France and Poland, the post-mining hazard is more based on the predisposition conditions (geology, geometry, method of extraction, geotechnic, hydrology, etc.) of the site than the probability of occurrence (the number of events par a period). In Greece, the monitoring of the mining site (dumps, slope, water level, etc.) is used to identify the potential post-mining hazards. Based on the in-site measurements, the site is classified from without risk to highly risky site. In last case, mitigation solutions can be suggested and carried out. In Germany, the methodology of the post-mining risk assessment can vary from one state to another, despite of the existing of a national law for managing the post-mining lands. Also, the assessment of hazards is generally based on the site characterization and the in situ measurement.

Thirdly, different international and European standards are related to post-mining hazard's assessment such as the standard for the water, the environment. The European directives are not systematically mentioned the post-mining hazards.

Fourthly, the application of the multi-hazard assessment and hazard interaction assessment approaches is very limited for mining sector. Only, in Germany such approach is used for taking into account the potential interaction between hazards.

The existing approaches used for natural hazards can be developed and used in the post-mining hazard assessment because certain similarities exist between natural and mining hazards, such as ground movement.

From the social and economic impact, it is clear that there is a real shortcoming of the risk assessment and the risk management. The partner experiences shown the mining and post-mining hazards have a large impact in coal region in transition. The occurrence of several hazards can increase this impact. This should be considered in the management and the sustainable development of coal region in transition.

POMHAZ will investigate this aspect through the development of the Decision Support System (DSS), taking integrating the social and economic dimensions.

6 Conclusion

Closed coalmine (ground mine, open-pit, dumps, lakes, etc.) can induce hazards and they could present a potential source of harm if they have potential social-economic impacts after the closure of the mines. One of the POMHAZ project objective is to identify, summarize and share the post-mining hazards in European coal mines. Additionally, the objective is to identify the potential interaction and to assess the multi-hazards.

A critical analysis of existing tools and methodologies between the different partners countries was carried out to highlight the common and different approaches to assess a single post-mining hazard.

Firstly, the partners have collected the information about the main post-mining hazards identified in their country and they have discussed the existing methodology and tools used for assessing the single post-mining hazards.

Then, the work done concerned the collected information, about existing tools dedicated to the study of the multi-hazards and multi-risks in general, methods and regulations for the identification, analysis, classification and assessment of post-mining hazards for their respective countries (France, Germany, Greek and Poland).

The outcome of this analysis has shown that for each country, the number of the hazards considered varies from one country to another. The main hazards are: ground movement, pollution, hydrological disturbance. But also, in Poland, the induced seismicity and radiation are considered as post-mining hazards related to coalmine.
The partners have presented examples illustrating the assessment of one single hazards. The examples have shown several common steps but also slight differences. Additionally, we have noticed that there was no scale to assess the post-mining hazards.
In Greece, the monitoring is the main tool used to assess the potential of the occurrence of hazards. Within the countries, the monitoring is mainly used after the mitigation of the post-mining-hazards.
The study shown that the multi-hazard assessment of post-mining hazards is not common. There are no real approaches, methodologies in the different European countries. However, we have noticed the correlation between hazards is generally considered. In Germany, they start to integrate them in the general risk assessment in the post-mining sites.
The European directives, mainly for water and pollutions, are very useful and certain countries use them for assessing the post-mining hazards.
In conclusion, the critical analysis clearly has highlighted the importance of multi-hazard analysis. Different tools used for multi-hazard analysis of natural hazards can be used in the context of the post-mining hazards, such as multi-hazard matrix, interaction organigram etc. The multi-hazard assessment will present important benefits for stakeholders and for the social and economic management of the multi-hazard and multrisk assessment and management manly for the land us.

The WP4 more precisely will deal with the social and economic aspect through the building of the DSS (Decision support system tool).

7 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.

Aller L., Bennett T., Lehr J.H., Petty R.J., Hackett G. (1987) DRASTIC: a standardized system of evaluating groundwater pollution potential using hydrogeological setting. EPA no. 600287035, USEPA, Washington, DC

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.

Ciurean R., Gill J., Reeves H. J., O'Grady S., Aldrige T. (2018). Review of environmental multihazards research and risk assessments. British Geological Survey Open Report, OR/18/057. 86pp.

Chen L., van Westen C. J., Hussin H., Ciurean R. L., Turkington Th., Chavarro-Rincon D., Shrestha D. P. (2016). Integrating expert opinion with modelling for quantitative multi-hazard risk assessment in the Eastern Italian Alps. Geomorphology 273 150–167.

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).

De Angelie S., Malamud B., Rossi L., Taylor F.E., Trasforini E., Rudari R. (2022). A multi-hazard framework for spatial-temporal impact analysis. International Journal of Disaster Risk Reduction 73 (2022) 1029229.

de Ruiter M. C., Couasnon A., van den Homberg M. J. C., Daniell J. E., Gill J. C., Ward P. J. (2020). Why we can no longer ignore consecutive disasters. Earth's Future, 8, e2019EF001425. https://doi.org/ 10.1029/2019EF001425.

Delmonaco G., Marhttini C., Spizzichino D. (2006). Report on new methodology for multi-risk assessment and the harmonisation of different natural risk maps. RMONIA project (Contract n° 511208). Applied multi-risk mapping of natural hazards for impact assessment. Deliverable 3.1.

Dilley M, Chen U RS Deichmann, Lerner-Lam A, Arnold M (2005) Natural disaster hotspots: a global risk analysis. In: Disaster Risk Management Series, 5, The World Bank

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

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.

Gill J.C., Malamud B.D. (2016). Hazard interactions and interaction networks (cascades) within multi-hazard methodologies. Earth Syst. Dynam., 7, 659–679. www.earth-syst-dynam.net/7/659/2016/. doi:10.5194/esd-7-659-2016.

Gill J.C., Malamud B.D. (2017). Anthropogenic processes, natural hazards, and interactions in a multi-hazard framework. Earth-Science Reviews 166 246–269.

Gill J.C., Malamud B.D. Barllas E. M. Noriega A. G. (2020). Construction of regional multi-hazard interaction frameworks, with an application to Guatemala. Nat. Hazards Earth Syst. Sci., 20, 149–180, 2020. https://doi.org/10.5194/nhess-20-149.

Gombert Ph. (2022). Etat des lieux à l'international de la problématique des échauffements de terrils. Ineris - 206841 - 2710892 - v1.0.

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

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.

Komendantova N., Mrzyglocki R., Mignan A., Khazai B., Wenzel F., Anthony Patt A., Fleming K. (2014). Multi-hazard and multi-risk decision-support tools as a part of participatory risk governance: Feedback from civil protection stakeholders. International Journal of Disaster Risk Reduction 8 50–67.

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 Z., Nadim F., Garcia-Aristizabal A., Mignan A., Fleming K., Luna B-Q. (2015). A three-level framework for multi-risk assessment, Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, DOI: 10.1080/17499518.2015.1041989 DNV GL, Høvik, Norway.
Liu B., Yim Ling Siu Y. L., Mitchell G. (2016). Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment. Nat. Hazards Earth Syst. Sci., 16, 629–642, 2016 www.nat-hazards-earth-syst-sci.net/16/629/2016/ doi:10.5194/nhess-16-629-2016.
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.
Lo Jacomo A., Han D., Champneys A. (2022). A model for generating multi-hazard scenarios Exploring the role of hazard cascades in a mountain catchment in China. Engineering and physical sciences research council.
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
Marcot N., Draperi N. (2009). Les risques naturels en Provence-Alpes-Côte d'Azur. ISBN: 978-2-7159-2472-7. 134 p.
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 Principles for documenting geological and engineering conditions for the purpose of mine closure, 2009, eds. Woźniak H., Nieć M., Warszawa, Ministry of Environment.
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.

Gildas Noury G., Perrin J., Luu L-H, Philippe P., Gourdier S. (2018). Rôle of flooding on sinkholes occurrence in covered karst terrains: case study of Orléans area (France) during the 2016 metrological event and perspectives for other kart environment. 15th Multidisciplinary Conference on Sinkholes.
and the Engineering and Environmental Impacts of Karst, Apr 2018, Shepherdstown, West Virginia, United States. ffhal-01706613
OECD (2022). The impact of Natural hazards on hazardous installations. oe.cd/natech. 18 p.
Odeh Engineers, Inc (2001) Statewide hazard risk and vulnerability assessment for the state of Rhode Island. Tech. rep., NOAA Coastal Services Center, http://www.csc.noaa.gov/rihazard/pdfs/rhdisl_hazard_ report.pdf, access 09 March 2010.
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.
Sigtryggsdottir F. G., Snæbjornsson J. Th., Grande L., Sigbjornsson R. (2015). Methodology for geohazard assessment for hydropower projects. Nat Hazards 79:1299–1331. Doi 10.1007/s11069-015-1906-4.
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 Natural Hazards & Infrastructure (ICONHIC 2019), 23-26 June 2019, Chania, Greece.
Salmon, R.; Franck, C; Lombard, Th.; Hadadou, R. (2019). Post-Mining Risk Management in France. 2019, Ineris - DRS-19-178745-02406A. https://www.ineris.fr/fr/post-mining-risk-management-france
Tieppolo M., Bacci M, Braccio S. (2018). Multihazard Risk Assessment for Planning with Climate in the Dosso Region, Niger. Climate 2018, 6, 67; doi:10.3390/cli6030067
Touili N. (2018). Management of multiples risks in urban areas: An integrated multi-risks analysis model for a general resilience. 2018 ISTE Open Science – Published by ISTE Ltd. London, UK – openscience.fr. 16 P.
Tubis A., Sylwia Werbinska-Wojciechowska S., Wroblewski A. (2020). Risk Assessment Methods in Mining Industry— A Systematic Review. Appl. Sci. 2020, 10, 5172; doi:10.3390/app10155172. http://www.mdpi.com/journal/applsci.
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.
van Westen C., Kappes M.S., Luna B.Q., Frigerio S., Glade T., Malet J-Ph. (2014). Medium-Scale Multi-hazard Risk Assessment of Gravitational Processes. Chap. 7. T. van Asch et al. (eds.), Mountain Risks: From Prediction to Management and Governance, Advances in Natural and Technological Hazards Research 34, DOI 10.1007/978-94-007-6769-0 7, © Springer Science + Business Media Dordrecht.
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-

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]
Guide for Mine Closure Planning" by Sánchez, L.E.; Silva-Sánchez, S.S.; Neri, A.C. (Brasília, 2014).
-"Risk Assessment Methods in Mining Industry" (available at: https://www.mdpi.com/2076-3417/10/15/517).
-International Council on Mining and Metals (ICMM) website (accessible at: https://www.icmm.com/en-gb/our-work/mine-closure).
-International Mining for Development Centre (IM4DC) website (found at: http://im4dc.org/).
-International Organization for Standardization (ISO) website (found at: https://www.iso.org/).-
-The European Mining Waste Directive (available at: https://eur-lex.europa.eu/eli/dir/2006/21/oj).
-"Leitfaden BBergAbf" (accessible at: https://www.bgr.bund.de/).
-Landesamt für Geologie und Bergwesen Sachsen (LAGB Sachsen) website (found at: https://www.lagb.sachsen.de/).