Post-Mining Multi-Hazards evaluation for land-planning

PoMHaz

WP3: Post-mining risks assessment methodology and decision support systems

D9 - Deliverable D3.1: Methodological guidelines about risk management

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Acronyms

DSS	Decision Support System
EAR	Elements At Risk
GDP	Gross Domestic Product
GIS	Geographic Information System
MCDM	Multi-Criteria Decision Making
MERIDA	Management of Environmental RIsk During and After mine closure
MHI	Multi-Hazard Index
MRV	Multi-Risk Value
POMHAZ	POst-Mining Multi-HAZards evaluation for land-planning
RFCS	Research Funds for Coal and Steel
TEXMIN	The impact of EXtreme weather vents on MINing operations
VI	Vulnerability Index
WP	Work Package

Executive Summary

This deliverable is part of the POMHAZ project, Post-Mining Multi-Hazards evaluation for land-planning.

The main objective of POMHAZ is to identify the interaction between the post-mining hazards for coalmines in Europe and to develop tools for facilitate the management of the post-mining hazards in coal region in transition.

In the POMHAZ project, the present deliverable is part of the WP3 that is dedicated to post-mining risk assessment methodology and decision support systems. This WP provides both methodology for assessing post-mining risks and the tools for decision-makers and coal communities facing multi-hazards and multi-risks. This deliverable is related to Task 3.1 " Development of the post-mining risks assessment ".

This deliverable presents a comprehensive methodology for multi-hazard risk assessment in post-mining areas, developed within the POMHAZ project. The goal of this methodology is to enable effective management and mitigation of risks arising from the complex interactions between natural, post-mining, and technological hazards in post-mining areas. This methodology provides a flexible and adaptable framework that can be applied to diverse European coal regions and beyond by integrating a semi-quantitative, mixed-methods approach.

The methodology is structured around a seven-step process, beginning with the identification of hazards and their initial intensities, followed by the analysis of hazard interactions through an interaction matrix. Multi-hazard scenarios are then developed, and the Multi-Hazard Index (MHI) is calculated, representing the cumulative intensity of hazard interactions. Vulnerability is assessed using a combined social and physical vulnerability index, which is then used alongside elements at risk (EAR) to calculate the Multi-Risk Value (MRV), providing a comprehensive measure of the socio-economic impacts of hazard scenarios. Key tools supporting the implementation of the methodology include spreadsheet-compatible tools, as well as GIS and Decision Support Systems (DSS) developed in WP3 and WP4. These tools enable data collection, analysis, and visualization of multi-hazard risks, ensuring consistency and enhancing decision-making capabilities for local authorities, planners, and other stakeholders in post-mining regions.

The methodology is adaptable to various case studies and regions, with a focus on post-mining areas in Europe. Real implementations, including locations in Germany and Greece, serve as case studies for the application of the methodology, offering valuable insights into its practicality and effectiveness in different contexts.

While the methodology provides a robust framework for risk assessment, challenges such as data quality, hazard interaction complexity, and the non-comparability of Multi-Hazard Indices across scenarios are acknowledged. Solutions, such as normalization techniques, are proposed to enhance the methodology's flexibility and ensure meaningful comparisons of risk levels.

The methodology presented in the deliverable represents a significant step forward in post-mining risk management, contributing to the broader objectives of the POMHAZ project. It aligns with the goals of the European Green Deal and Just Transition by promoting sustainable land management, fostering resilience, and supporting the transition of coal regions toward a carbon-neutral economy. The methodology equips stakeholders with the tools and knowledge needed to address multi-

hazard risks in post-mining areas, contributing to the long-term socio-economic and environmental stability of these regions.

Deliverable links

Moreover, the implementation of the methodology is supported by resources developed in WP3 and WP4, which focus on refining the multi-hazard assessment framework and enhancing the GIS and DSS systems. WP3 contributes to this effort through Deliverables D3.2: DSS specifications related to post-mining hazard management (DMT-THGA) and Deliverable D3.3: DSS tool and report detailing its application (DMT-THGA). WP4 complements these efforts with additional deliverables, including Deliverable D4.2: Implemented interfaces, database, and DSS toolbox (TU BAF), Deliverable D4.3: GIS-based Python toolbox for the implementation of the post-mining hazards (TU BAF), and Deliverable D4.4: Coupled GIS-DSS module with an intuitive interface and guide document, documented in a verification case (GIG, TU BAF, CERTH). These deliverables collectively ensure the methodology's practical application, providing users with comprehensive tools and resources for multi-hazard risk assessment in post-mining areas.

1 Introduction

1.1 Purpose of the methodological guidelines

These methodological guidelines were developed as part of the POMHAZ project to address the need for robust and systematic approaches to multi-hazard risk management in abandoned coal mining areas across Europe. The guidelines presented in this deliverable serve as a foundation for assessing, managing, and mitigating post-mining risks, which are generated by interactions among post-mining hazards affecting environmental stability, urban development, and socio-economic resilience within post-mining-impacted communities. These guidelines aim to support a wide range of stakeholders - such as local governments, coal communities, planners, and industry professionals - in making informed and sustainable land-use and planning decisions in post-mining areas. This support is offered by detailing each step of a comprehensive multi-hazard risk assessment and management process, which considers both immediate and long-term impacts.

Furthermore, these guidelines are intended to facilitate the application of advanced tools and techniques, including Decision Support Systems (DSS) and Geographic Information System (GIS), in identifying, prioritizing, and addressing the complex hazard interactions present in post-mining environments.

The guidelines help ensure that decisions are based on a thorough, data-driven understanding of multi-hazard conditions, by combining DSS and GIS with multi-hazard risk approaches. The guidelines emphasize a multi-hazard approach, recognizing that abandoned mining sites often pose interconnected risks, which must be considered in an integrated manner to achieve effective risk reduction.

A core principle of these guidelines is to emphasize a multi-hazard risk approach, recognizing that abandoned mining sites often pose interacting hazards, which must be considered in an integrated manner to achieve effective risk reduction. This approach involves assessing the cumulative impacts of multiple hazards, rather than addressing each hazard separately; to better understand the complex dynamics of post-mining areas. For example, land subsidence might affect water contamination patterns, or might exacerbate slope instability risks, necessitating a holistic perspective to address these challenges.

In addition to addressing hazards in the post-mining area, these guidelines support the broader objectives of the European Green Deal and the transition to a carbon-neutral economy. Decarbonization, a cornerstone of European policy, which prioritizes phasing out coal and other fossil fuels, directly affecting coal regions and accelerating their transformation. This shift presents both challenges and opportunities: abandoned coal mines and their associated hazards not only pose environmental and safety risks but also offer potential for sustainable repurposing, such as the transformation of post-mining areas into regions for renewable energy generation, including solar, wind, and geothermal projects. Furthermore, this approach supports the principles of a Just Transition, ensuring that repurposing taking into account hazard interaction would not impair economic development in former coal regions. Abandoned mines often lie within regions that depend heavily on coal for economic stability. As mines close and regions decarbonize, local communities face economic disruptions, job losses, and socio-economic vulnerability.

These guidelines seek to support decision-making that prioritizes social resilience and economic regeneration in coal-affected areas, by integrating principles of a Just Transition. This includes promoting sustainable development options and creating conditions for new facilities that can offer stable, long-term employment for former coal industry workers. To achieve a Just Transition, the guidelines advocate for risk management strategies that not only reduce post-mining hazards but also foster community engagement and inclusive planning processes. This ensures that the perspectives and needs of affected communities are integral to planning and decision-making. By involving local communities and stakeholders early in the planning phases, the guidelines support a collaborative approach that aligns hazard management with community priorities, helping to mitigate social disruptions and fostering a sense of ownership and agency among residents.

1.2 Scope

The scope of these guidelines encompasses the management of multi-hazard conditions and the assessment of multi-risks in post-mining areas, focusing on providing a flexible, adaptable, and semi-quantitative methodology. These guidelines focus on abandoned lignite and coal mines across Europe, addressing a broad spectrum of post-mining hazards such as those included in the database of the Deliverable D2.1 of the POMHAZ project and divided in four categories: ground movement, environmental pollution, hydrological issues/water disturbances, and gas/fire. They deliver a practical multi-hazard risk assessment framework tailored to the unique needs of post-mining areas by supporting data customization through DSS and prioritizing hazard interactions within a European coal basin context.

The methodology is primarily designed to serve as a tool for European coal regions as they address the complex challenges posed by abandoned mining sites. The methodology is applied at the scale of a mining basin and its surrounding community, taking into account the complex interactions between the post-mining hazards and their related multi-risks that affect the post-mining areas, the local communities, the population, and the environment.

The guidelines are intended for use in post-mining areas where multiple hazards may exist, posing multi-risks to different categories of elements exposed to risk. Although developed with a primary focus on European coal basins, which are the central focus of the current project, this methodology can potentially be adapted to post-mining areas globally, especially those facing similar challenges. These guidelines are particularly relevant for regions that lack comprehensive data on hazard interactions, as the semi-quantitative approach allows for effective multi-hazard risk assessment and decision-making even when data limitations exist. While the guidelines are versatile, it is essential to recognize that they were tailored specifically to meet the needs and conditions of European post-mining areas.

Within the POMHAZ project, the guidelines will be applied to several case studies in European post-mining areas during WP5, providing an opportunity to test and refine the methodology under diverse conditions. However, it is important to acknowledge certain limitations within the scope of these guidelines. Although the methodology is adaptable, it is not designed to address all possible hazards associated with non-coal mining activities, nor does it provide a purely quantitative risk analysis. Users should also consider that while the DSS component allows for some level of data customization, the effectiveness of the methodology depends on the quality and relevance of the data inputs provided.

To offer a clear and practical framework, during the POMHAZ project these guidelines are incorporated in a multi-hazard risk methodology integrated in a GIS and Decision Support System (DSS). This multi-hazard risk method allows for the analysis and prioritization of various hazards, their interactions, and multi-risks, ensuring that all relevant factors are considered holistically. End-users can make decisions based on a comprehensive understanding of the post-mining risks by analyzing hazard interactions. This approach is especially critical given the unique interplay between different hazards in post-mining environments, where the consequences of one risk factor (e.g., subsidence) may intensify the impacts of another (e.g., induced-seismicity), creating complex risk landscapes.

The Decision Support System (DSS) provides the flexibility and adaptability of the guidelines, allowing end-users to input national standards, specific local data, and case study specific information into the multi-hazard risk assessment framework. The DSS empowers users to adapt the methodology to their particular context, making the guidelines broadly applicable across diverse post-mining areas by enabling the customization of input parameters. This customization is essential for coal mining basins in Europe, where data availability, hazard types, and socio-economic factors may vary significantly from one location to another.

Given the nature of multi-hazard risk in post-mining areas, this methodology adopts a semi-quantitative approach. A semi-quantitative approach involves combining both qualitative insights and quantitative data, which is particularly useful in situations where comprehensive quantitative data may be lacking. This methodology was selected due to the inherent challenges in obtaining precise data on hazard interactions and the varying types of hazards involved in post-mining areas. The guidelines provide a flexible framework that can function effectively in data-limited environments by utilizing a semi-quantitative approach, allowing for multi-hazard risk assessment even when detailed quantitative measurements are unavailable. The semi-quantitative approach also facilitates the incorporation of local knowledge, expert opinions, and approximate data, which can enhance the reliability of the risk assessment when precise measurements are not feasible.

As a result, these guidelines can deliver valuable multi-risk management insights to decision-makers who may be operating with constrained resources or incomplete datasets, typical challenges in post-mining contexts.

1.3 Background

The Research Fund for Coal and Steel (RFCS) program plays a pivotal role in advancing research and innovation in areas related to decarbonization, just transition, and the sustainable reclamation of abandoned mines. The RFCS provides funding for projects that address environmental, social, and economic challenges in coal and steel regions.

The POMHAZ project builds upon the foundation laid by earlier RFCS projects, particularly MERIDA and TEXMIN. MERIDA project focused on managing environmental risks during and after mine closure. The main objective of MERIDA was to develop guidance on the necessary investigations required to create effective mine closure plans. TEXMIN, which aimed to identify and evaluate the environmental impacts on operating, closed, and abandoned mines caused by extreme weather events. TEXMIN provided valuable insights into managing mining-related hazards exacerbated by climate change.

While MERIDA emphasized the development of comprehensive mine closure plans, POMHAZ takes a step further by focusing on the interactions between different hazards and their relevant risks in post-mining areas. The core idea of POMHAZ was born from the need to systematically analyze and manage these hazard interactions to mitigate multi-risks effectively.

A critical gap identified in the domain of post-mining management is the lack of comprehensive multi-hazard risk assessment methodologies tailored to post-mining hazards. This absence has significant implications, particularly given the documented cascading effects observed in abandoned mining areas. Cascading effects occur when one primary hazard—such as subsidence or landslide - triggers secondary hazards, such as hydrological disturbances, creating a chain reaction that amplifies impacts on the affected area. For instance, subsidence could cause flooding, which in turn might lead to soil contamination, exacerbating environmental and socio-economic vulnerabilities. These cascading effects result in complex, interacting hazards that are not adequately addressed by traditional single-hazard approaches. This oversight highlights the importance of adopting a multi-hazard perspective, which considers both direct and indirect interactions between hazards to mitigate compounded risks effectively.

Through this deliverable, POMHAZ offers actionable insights for stakeholders, empowering local governments, planners, and industries to manage multi-hazard risks while promoting sustainable development by bridging the gap between research and practical applications. The integration of cascading effects into the multi-hazard risk framework marks a significant advancement in addressing the challenges posed by abandoned mining areas. Recognizing how one hazard can amplify the impact of another - creating a feedback loop of risks - enables the POMHAZ methodology to provide a more realistic and actionable understanding of the risks involved. This innovative approach not only ensures that immediate hazards are addressed but also anticipates and mitigates secondary risks, reducing the potential for unforeseen consequences and enhancing the resilience of post-mining communities.

2 Objectives

The objectives of this deliverable reflect the broader goals of the POMHAZ project, which seeks to enhance the management of post-mining hazards in abandoned coal mines through a comprehensive and integrated methodology. By addressing the complexities of multi-hazard conditions, the project aims to equip stakeholders with tools and knowledge that are practical, adaptable, and robust enough to manage multi-risks effectively, while ensuring sustainable land-use practices and planning for post-mining areas.

The specific objectives of this methodology build upon the overall goals, breaking them into actionable components that address the unique challenges of multi-hazard risk assessment and management in post-mining areas. These objectives include:

1. <u>The development of consistent methodologies across hazards</u>
   The methodology aims to harmonize approaches to risk assessment for different hazards, ensuring consistency in how hazards are identified, evaluated, and managed. This alignment is crucial for creating a unified framework that accommodates the complexity of multi-hazard conditions.

2. <u>The establishment of a systematic approach to multi-risk assessment</u>
   A core objective is to develop a step-by-step approach to multi-hazard risk assessment that incorporates technical, environmental, and socio-economic factors. This systematic framework ensures that all relevant dimensions of risk are considered holistically.

3. <u>Account for hazard interactions</u>
   The methodology emphasizes the importance of understanding and addressing the spatial and/or temporal interactions between hazards. For example, subsidence can trigger water disturbances or slope movement, leading to cascading effects. The methodology provides a more comprehensive representation of risk levels by considering these interactions.

4. <u>Incorporation of mitigation techniques into a holistic view</u>
   The methodology evaluates the impact of mitigation measures not only on individual hazards but also on their interactions. This approach ensures that mitigation efforts do not inadvertently exacerbate other risks, providing a global view of multi-hazard management.

5. <u>Provision of resources for future land management and spatial planning</u>
   The project aims to produce guidance documents and tools that help local authorities anticipate hazard interactions and prepare for the transition from active mining to post-mining phases. These resources are critical for integrating multi-hazard considerations into long-term land management practices.

6. <u>Adaptability and customization for diverse contexts</u>
   While the methodology is proposed and designed for European coal regions, it incorporates a level of adaptability that allows its application to other post-mining contexts. The DSS based on the multi-hazard risk method enables end-users to input localized data, aligning the methodology with specific geological, environmental, and socio-economic conditions.

7. Guidelines for stakeholder integration
   To facilitate implementation, the methodology provides clear, actionable guidelines for local authorities. These guidelines empower stakeholders to integrate multi-hazard approaches into existing practices, improving the protection of communities and infrastructure from hazard interactions and their relative multi-risks.

8. Enhancement of knowledge transfer and collaboration

   The methodology fosters collaboration among stakeholders by encouraging the exchange of practices and understanding of hazard interactions. This collaborative approach ensures the methodology's practical utility and supports its adoption across different contexts.

The methodology delivers a practical, systematic, and adaptable framework that empowers stakeholders to manage multi-hazards effectively in post-mining areas by addressing these specific objectives. It bridges the gap between technical analysis and real case studies application, ensuring that local authorities and communities can make informed decisions to enhance resilience and sustainability in coal mining areas transitioning to post-mining phases.

3 Methodological framework

3.1 Theoretical background

The concept of multi-hazard risk assessment is grounded in understanding the interconnectedness and interdependencies among different hazards, especially as they interact with vulnerabilities and affect various risk elements. This approach contrasts significantly with single-hazard risk assessment, which considers each hazard independently, assuming no interactions or compounded impacts between them. In multi-hazard risk analysis, however, it is essential to consider how multiple hazards influence each other and how their combined effects may exacerbate vulnerabilities in a given area. This is particularly relevant in post-mining areas, where a combination of hazards frequently coexists, creating a unique and complex risk landscape. An appendix with the definitions of the key terms used in the deliverable's methodology is provided in Appendix B.

The methodology used for multi-hazard analysis must be flexible enough to incorporate the complex interactions and adaptable to varying types and severities of hazards. Generally, there are three primary approaches to multi-hazard risk analysis: qualitative, semi-quantitative, and quantitative. Each of these methodologies offers distinct benefits and faces specific challenges, making the choice of approach dependent on the research objectives, data availability, and the specific characteristics of the analysis.

<u>Qualitative Methods:</u> Qualitative approaches rely on expert knowledge and engineering judgment to identify potential hazard interactions. Tools such as interaction matrices (Greiving (2006), De Pippo, Donadio et al. (2008), Gill and Malamud (2014)), diagrams (López-Saavedra and Martí (2023), Mohamed Marwan, Christian et al. (2023)), and decision trees (Neri, Le Cozannet et al. (2013), Terzi, Torresan et al. (2019)) are commonly used to characterize and visualize these relationships. In multi-hazard studies, these methods can employ color scales or descriptive terms to represent interactions between hazards. Although qualitative methods provide a simplified view of the hazard landscape, they are valuable for initial assessments, especially when data is limited or when visual representation of interactions is necessary for communication with stakeholders. However, because qualitative methods rely on subjective judgments, they may lack the rigor needed for detailed risk quantification and are often supplemented by more objective analyses.

<u>Semi-Quantitative Methods:</u> Semi-quantitative methods bridge the gap between qualitative insights and quantitative precision. These methods combine engineering judgment with computational analyses, using in several researches multi-criteria decision-making (MCDM) frameworks and GIS tools (Bathrellos, Skilodimou et al. (2017), Skilodimou, Bathrellos et al. (2019), Aksha, Resler et al. (2020), Rehman, Song et al. (2022), Wu, Zhang et al. (2022)) to assess multi-hazard conditions. Semi-quantitative methods often transform hazard interactions into indicators or assign relative weights to various hazards, reflecting their potential impact on the study area (De Pippo, Donadio et al. (2008), Barrantes (2018), Liu, Han et al. (2021), Chen, Zhao et al. (2023)). This approach is advantageous in scenarios where data availability may be moderate but insufficient for full quantitative analysis. Semi-quantitative methods provide a flexible framework that can adapt to different hazard types, interactions, and scenarios by incorporating both objective data and expert assessment. Furthermore, spatial analysis through GIS software enables these methods to account for spatial relationships and visualize multi-hazard risks across the landscape.

Quantitative Methods: Quantitative approaches use statistical and probabilistic tools to analyze rigorously multi-hazard interactions, typically requiring substantial data. Techniques like Bayesian networks (F. Nadim and Liu (2013), Terzi, Torresan et al. (2019), Chang, Dou et al. (2022)), Copula functions (Ming, Xu et al. (2015), Tilloy, Malamud et al. (2020)), conditional probabilities (Marzocchi, Garcia-Aristizabal et al. (2012), Neri, Le Cozannet et al. (2013), Liu, Siu et al. (2016)), and Monte Carlo simulations Mignan, Wiemer et al. (2014) are employed to model complex dependencies and to calculate precise risk estimates. Quantitative methods provide the highest level of detail and can produce probabilistic models that account for uncertainties and cascading effects. However, they demand comprehensive datasets and computational resources, which are often unavailable in post-mining contexts due to the challenges of data collection and the inherent complexity of hazard interrelations in these environments. In post-mining areas, data limitations often restrict the applicability of purely quantitative methods, making them most feasible when data coverage is high or when paired with semi-quantitative approaches to maximize both accuracy and adaptability.

The selection of a multi-hazard risk methodology for post-mining analysis is critical, requiring careful evaluation of qualitative, semi-quantitative, and quantitative approaches. Indicator-based methods have emerged as an effective solution. These methods are adaptable to data-limited post-mining areas. By prioritizing interventions based on vulnerability and exposure levels, they support targeted resilience strategies, particularly in regions with socio-economic challenges and deteriorating infrastructure. However, challenges such as data quality and availability can limit accuracy. Hybrid methods, incorporating indicator-based analysis with probabilistic models like Bayesian networks, offer enhanced robustness by combining empirical data with expert judgment. This approach enables a nuanced understanding of hazard interactions, making indicator-based methodologies a practical and comprehensive tool for managing multi-hazard risks in post-mining areas.

3.2 Methodology overview

In this project, the multi-hazard risk methodology is based on a semi-quantitative, mixed-methods approach. This type of methodology was selected for its adaptability to post-mining areas, where different types of hazards - natural, post-mining, and technological - can coexist and interact, creating multi-hazard conditions. Given the inherent difficulties in precisely quantifying interactions among different hazard types, a semi-quantitative approach offers the flexibility required to express these interconnections effectively. Additionally, the lack of extensive data in many post-mining areas further supports the choice of a semi-quantitative method, which can work with both available quantitative data and qualitative insights from experts. This mixed-method approach combines two semi-quantitative techniques: one for multi-hazard analysis and another for vulnerability assessment. These techniques use both objective data, such as hazard maps and hazard frequency return periods, and subjective insights generated by experts based on their knowledge and experience.

Data collection for the identified hazards in each post-mining area relies on existing national or European hazard maps, which are quantitative by nature. However, as a semi-quantitative method is applied, some data is also generated from expert input. This inclusion of expert assessments allows for more nuanced hazard interaction analysis, accommodating gaps in quantitative data and addressing local conditions. Together, these components support a framework that remains adaptable to various post-mining case studies, providing a robust basis for comprehensive multi-hazard risk assessment.

Various methods are employed for the analysis of multi-hazard interactions. The chosen indicator-based approach, partial multiplication factor method, for multi-hazard analysis was selected for its adaptability and flexibility to fit any post-mining case study. This method's core principle is to enhance the assessment of each hazard's intensity when it interacts with others, effectively capturing the compounded severity and increased impact on post-mining area in each scenario. Similar criteria guided the selection of the indicator-based approach for vulnerability analysis, which comprehensively addresses both physical and social vulnerabilities of the case study. This approach allows for a holistic risk assessment that reflects the specific dynamics of post-mining areas, providing a nuanced understanding of both multi-hazard scenarios and their potential impacts on vulnerable communities.

The application of the methodology on the multi-hazard risk assessment follows four main components, as illustrated in the flowchart of Figure 1. These four components are the core of the seven step methodology outlined in the current deliverable.

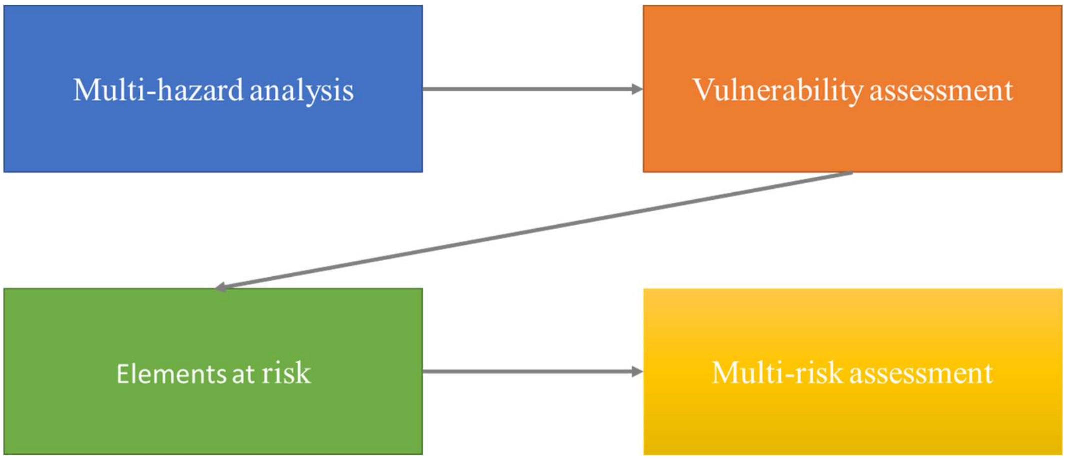

Figure 1: Methodological flowchart for multi-hazard risk assessment in post-mining areas

- Multi-hazard analysis: Hazards in each post-mining area are identified, and data is collected from various sources to assess each hazard's potential intensity. Interactions between hazards are analyzed and depicted in an interaction matrix (interaction level). This matrix, along with hazard assessment and specific indicators, is then used to calculate the multi-hazard index (MHI) for each interaction chain, resulting in distinct multi-hazard scenarios for the post-mining area under study. The output of this step is a multi-hazard index for each scenario, which quantitatively reflects the relative overall intensity of its multi-hazard scenario.
- Vulnerability assessment: Both physical and social vulnerabilities of the post-mining area are calculated. This stage uses a well-established, indicator-based method widely employed in social vulnerability and resilience calculations. This approach enables a more comprehensive vulnerability index (VI), covering structural, demographic, and socioeconomic factors that influence how communities in post-mining areas may respond to hazard impacts, by including both physical and social elements.
- Elements at risk: This is the most straightforward component, where end-users provide data on elements. These elements are quantified based on national standards and entered through the DSS, resulting in an output that expresses the economic value of the assets and infrastructure exposed to hazards within the area. This information is critical, as it enables the integration of economic considerations into the multi-hazard assessment.
- Multi-risk assessment: several land-use scenario can be studied in this step, the multi-risk value is calculated for each scenario identified in the multi-hazard analysis. For each scenario, the

multi-risk value is derived by combining the multi-hazard index, the vulnerability index of the case study, and the economic value of elements at risk. This product yields a multi-risk value expressed in monetary terms, allowing decision-makers to assess the socio-economic impact of each scenario. This approach enables a meaningful and actionable assessment of multi-risk levels, supporting targeted mitigation strategies for post-mining areas.

The choice of a semi-quantitative approach in this methodology is primarily driven by the need for flexibility and adaptability in post-mining contexts, where precise quantitative data may be sparse, and multiple interdependent risk factors must be considered. This approach balances objectivity with subjectivity, utilizing both data-driven techniques and expert input to develop a multi-hazard risk framework that can address the unique complexities of each area. The combination of methodologies, allows for a robust and balanced assessment, ensuring that each hazard and vulnerability component is weighted appropriately to reflect its impact within a complex, data-limited environment.

4 Step-by-Step process

To guide users through the POMHAZ multi-hazard risk assessment method, this section provides a structured, step-by-step approach for evaluating multi-hazard risks in post-mining areas. The methodology builds upon prior work, including the identification of post-mining hazards, which serves as the input for the first step (hazard susceptibility) and was developed in Deliverable D2.1. Additionally, the concept of using an indicator-based multi-hazard method was introduced in Deliverable D2.2, while the application of indicators was further detailed in Deliverable D2.3. This methodology systematically assesses hazard susceptibility, identifies hazard interactions, and quantifies cumulative impacts across multiple hazards and vulnerable elements. Each step builds upon the previous one, facilitating an organized analysis that captures the complexity of post-mining areas with their hazard interactions. This approach enables decision-makers to derive a comprehensive multi-risk value, helping them prioritize and manage hazards effectively. The following flowchart in Figure 2 illustrates the seven steps of the methodology: beginning with hazard susceptibility (Step 1) and progressing through each phase to the final calculation of the multi-risk value (Step 7).

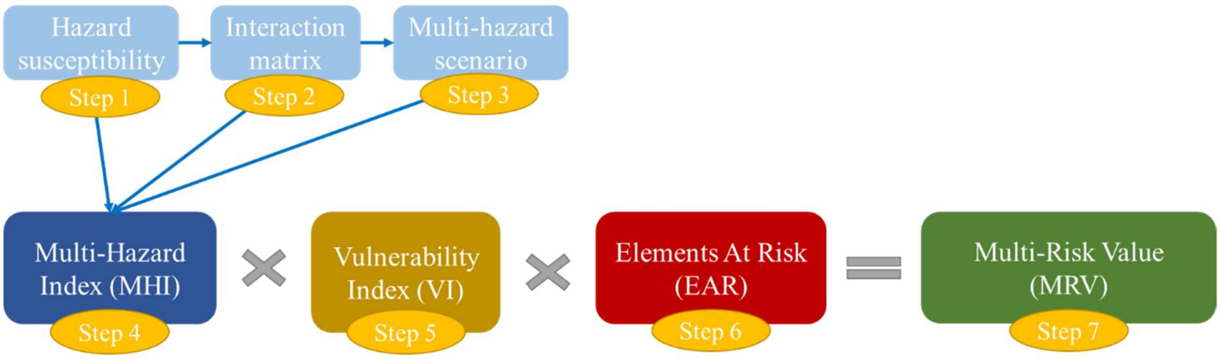

Figure 2: Flowchart of POMHAZ's multi-hazard risk assessment method

Step 1: Hazard susceptibility

In the first step of the POMHAZ multi-hazard risk assessment methodology, users establish hazard susceptibility by identifying relevant hazards and assessing their potential initial intensity within the study area. This process relies on the project's compiled database from Deliverable D2.1, which contains a comprehensive list of (post-)mining hazards developed with input from all project partners. This list is available in Appendix A. It serves as a reference to ensure consistent hazard identification across case studies. In addition to this list, each user can identify specific natural and anthropogenic hazards relevant to their study area, ensuring localized context and relevance.

After selecting the applicable hazards, users assess the susceptibility of each hazard to better understand its potential impact on the post-mining area. This involves gathering local data such as hazard maps, historical records, governmental reports, return period, and other relevant documentation that detail the occurrence and characteristics of each hazard. Based on this data, each hazard is then assigned an initial intensity level from 1 to 3 (1=low/ 2=medium/ 3=high), following an increasing scale, where 1 represents minimal intensity and 3 represents high intensity (Table 1).

Table 1: Quantitative and qualitative expression of hazard initial intensity

Quantitative expression of hazard intensity	Qualitative expression of hazard intensity
1	Low
2	Medium
3	High

Expected Output

The output of this step should be the Table 2, which lists all the identified hazards of the case study, along with their types and intensities, as determined through the hazard susceptibility process.

The assigned susceptibility levels provide a foundational understanding of each hazard's significance and potential impact in the region, setting the stage for analyzing hazard interactions in Step 2. This structured approach to hazard susceptibility ensures a uniform framework for multi-hazard assessments, enabling users to evaluate the potential risks effectively and systematically in the context of post-mining areas.

Table 2: Hazard susceptibility output summarizing identified hazards, their types and intensities

Hazard	Type	Intensity
Identified hazard 1	Natural/ Post-Mining/ Technological	1-3
Identified hazard 2	Natural/ Post-Mining/ Technological	1-3
…	…	…
Identified hazard n	Natural/ Post-Mining/ Technological	1-3

Step 2: Interaction matrix

The interaction matrix is a structured tool used to evaluate and quantify the interactions between the identified hazards from Step 1. This step focuses on understanding how a primary hazard can influence or trigger a secondary hazard. The interaction matrix provides a visual and quantitative framework to capture these relationships, which is essential for multi-hazard analysis. The process for constructing and applying the interaction matrix is as follows:

1. Define the interaction matrix layout:
   The matrix is designed in a tabular format where the rows and columns represent the identified hazards. The identified hazards from Step 1, along with their types, are placed on both the vertical (row) and horizontal (column) axes (see Figure 3).

   - The vertical axis represents primary hazards (those that trigger or influence others).
   - The horizontal axis represents secondary hazards (those that are affected by or triggered by the primary hazards).
2. Assign interaction levels:
   Each cell ij in the matrix represents the interaction level between the primary hazard i and the secondary hazard j for the specific case study. The interaction levels are categorized into three levels, each represented by a specific color for easy interpretation:

   - Green (Low Interaction): Minimal influence or triggering potential.
   - Orange (Medium Interaction): Moderate influence or triggering potential.
   - Red (High Interaction): Significant influence or triggering potential.

   Cells where there is no interaction between hazards are assigned white, while diagonal cells (where a hazard would interact with itself) are marked grey and excluded from the analysis (see Figure 3).

3. Use established criteria for assigning levels:
   Interaction levels are assigned based on expert judgment, past studies, hazard occurrence records, or other relevant data. The levels should reflect the likelihood and impact of the interaction between each pair of hazards.

4. Document and Visualize Results:
   The completed matrix visually communicates the interdependencies among hazards, highlighting critical interactions that require attention in the subsequent steps.

5. Template and references:
   A template for constructing the interaction matrix is provided in this deliverable to standardize the format across case studies. The method for creating the interaction matrix is adapted from Liu, Han et al. (2021). The Figure 3 illustrates the structure of the interaction matrix. The arrows in the upper matrix indicate that Hazard 1 (from the vertical axis) triggers Hazard n (from the horizontal axis), represented in cell 1n, with a low interaction level (green cell) in the lower matrix. Similarly, Hazard n triggers Hazard 1 with a medium interaction level (orange cell).

Expected Output

The expected output of step 2 is a completed interaction matrix that details the interaction levels among all the identified hazards.

By applying this step systematically, users can clearly understand the interplay between hazards in their specific post-mining case study, forming the foundation for constructing multi-hazard scenarios in the next step.

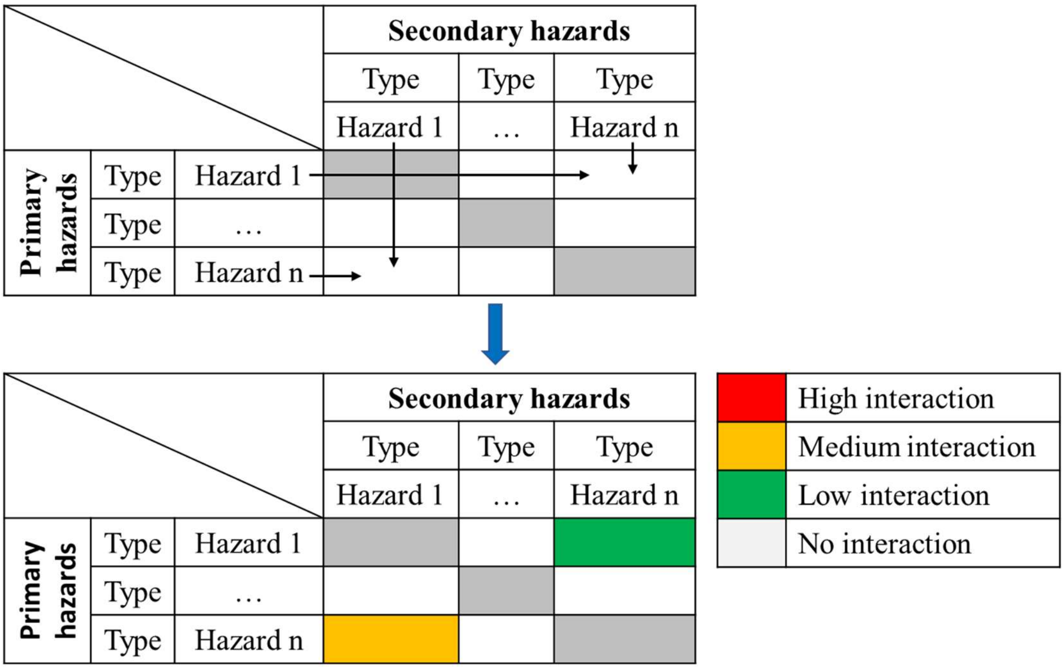

Figure 3: Structure of the interaction matrix showing the interaction levels between hazards, with colored cells indicating the level of interactions: low (green), medium (orange), and no interaction (white). Diagonal cells are grey, indicating hazard interacting with itself and are excluded from the analysis.

Step 3: Multi-hazard scenario

The third step in the multi-hazard risk methodology involves constructing multi-hazard scenarios, which are sequences of interrelated hazards where a primary hazard triggers secondary hazards, leading to a cascading effect. Primary hazards are the initial events that directly cause damage, serving as the starting hazard in a sequence of events. Secondary hazards occur as a sequence of the primary hazards, amplifying the overall impact. These scenarios provide a structured representation of how hazards interact and evolve, enabling a realistic assessment of their combined impacts.

The foundation for developing multi-hazard scenarios comes from the interaction matrix constructed in Step 2. Each scenario is based on the interactions identified in the matrix, ensuring that only plausible and data-supported sequences are considered. A scenario must involve at least two hazards, where a primary hazard (e.g., flooding) triggers or influences a secondary hazard (e.g., landslide), and potentially additional hazards (e.g., structural collapse).

The number of potential multi-hazard scenarios is determined by the identified interactions within the matrix. For instance, if numerous hazards and significant interdependencies exist, the analysis may yield a wide range of possible scenarios. However, the focus should remain on constructing realistic and representative scenarios. This ensures that the assessment is grounded in practical and likely hazard chains rather than theoretical or overly complex combinations. The creation of each scenario follows a sequential approach. Starting from a primary hazard, the analysis traces interactions with subsequent hazards as defined by the interaction matrix. The strength and nature of each interaction guide the inclusion of hazards in the scenario. Hazards with no interaction are excluded.

Figure 4 illustrates the creation of multi-hazard scenarios using a tentative interaction matrix with four hazards. Arrows highlight how interactions between hazards lead to the formation of four distinct scenarios. These visual connections represent the pathways through which one hazard triggers another, clarifying the development process. The output of this step is a table that organizes and illustrates the identified scenarios, providing a clear overview of their structure and relationships. Table 3 presents the multi-hazard scenarios derived from the interactions illustrated in Figure 4.

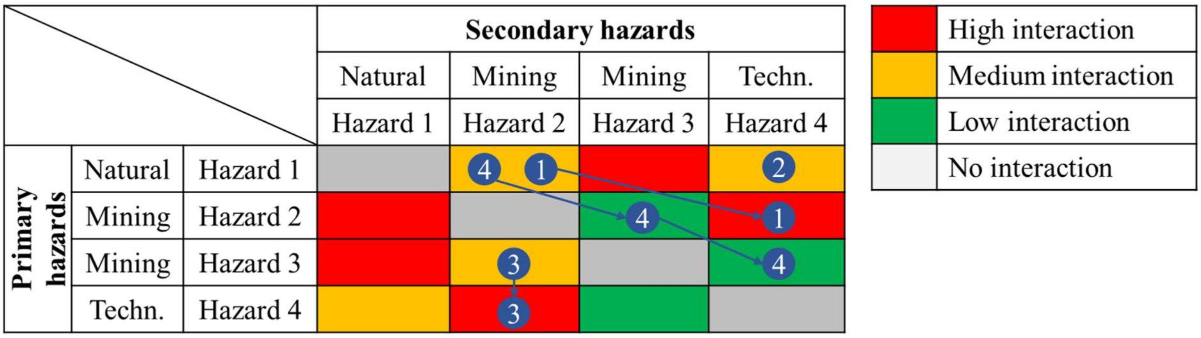

Figure 4: Illustration of a tentative interaction matrix showing the creation of multi-hazard scenarios. Arrows indicate the interactions between hazards, while the matrix structure highlights the pathways forming each scenario.

Table 3: Multi-hazard scenarios

No.	Scenario
1	Hazard 1 → Hazard 2 → Hazard 4
2	Hazard 1 → Hazard 4
3	Hazard 3 → Hazard 2 →Hazard 4
4	Hazard 1 → Hazard 2 →Hazard 3 →Hazard 4

For the 3rd scenario, the Hazard 3 triggers Hazard 2. Then, Hazard 2 triggers Hazard 4.

Expected Outputs

The expected output of step 3 is a list of well-defined scenarios that outline the sequences of interrelated hazards and illustrating their cascading effects.

Step 4: Multi-hazard Index (MHI)

The Multi-Hazard Index (MHI) is a crucial component of this methodology, representing the cumulative intensity of a multi-hazard scenario. It quantifies the overall severity of interacting hazards by considering the adjusted intensities of individual hazards within each scenario. This step enables a comprehensive evaluation of multi-hazard conditions, accounting for the increased intensity resulting from hazard interactions.

Concept of Adjusted Intensity

The adjusted intensity is a recalibrated measure of a hazard's initial intensity, incorporating the influence of its interactions with subsequent hazards in a specific scenario. The principles for adjusting intensities are derived from research contributions during Task 2.3 of this project. These principles align with methodologies detailed in Deliverable D2.3 and relevant research literature related to indicator-based methods. The adjusted intensity for each hazard is calculated using the following equation:

$$\mathrm{H}_{\mathrm{adj-i}} = \mathrm{H}_{\mathrm{ini-i}} \times \prod_{1}^{n} L_k$$

where:

$\mathrm{H}_{\mathrm{adj-i}}$: adjusted hazard level of hazard i, the recalibrated intensity of hazard i in the scenario.

$\mathrm{H}_{\mathrm{ini-i}}$: initial hazard intensity of hazard i, assigned in Step 1.

L_k : adjusted principle, a value derived from interaction level between hazard i and hazard j (as described in Step 2); k varying from 1 to 3.

The multiplication with adjustment principles can involve up to two factors (n up to 2) for a hazard situated between two others: one factor accounts for the interaction with the preceding hazard, and the other accounts for the interaction with the subsequent hazard.

Interaction Levels and Adjustment Factors

Interaction levels are categorized into three qualitative levels - low, medium, and high - and are associated with corresponding quantitative adjustment factors. Table 4 illustrates the translation of interaction levels into adjustment principles.

Table 4: Adjustment principles for hazard-adjusted intensity calculation

Qualitative Description	Adjusted principle (L_k)
Low	1
Medium	2
High	3

White cells in the interaction matrix (indicating no interaction) correspond to an adjustment principle of 0, meaning the hazard's intensity remains unchanged for that interaction.

Calculation of the Multi-Hazard Index

For each scenario, the MHI is calculated by summing the adjusted intensities of all hazards included in the scenario:

$$\mathrm{MHI} = \sum_{1}^{n} (\mathrm{H}_{\mathrm{adj-i}})$$

The resulting MHI provides a single value representing the compounded intensity of a multi-hazard scenario. A higher MHI indicates a greater potential impact due to the interplay of hazards.

Expected Outputs

The output of this step includes:

1. A table detailing the adjusted intensities of hazards for each multi-hazard scenario.
2. The calculated MHI for each scenario, representing the aggregated intensity.

This step bridges the assessment of individual hazard intensities from Step 1 with the broader analysis of multi-hazard scenarios, serving as a foundational metric for subsequent steps in the methodology.

Step 5: Vulnerability Index (VI)

The Vulnerability Index (VI) represents the combined assessment of social and physical vulnerability in post-mining areas. It provides a comprehensive understanding of the potential impacts of multi-hazard phenomena by considering both societal and infrastructural elements. This step adopts and adapts the framework of the Social Vulnerability Index proposed by Cutter, Boruff et al. (2012) to address the unique characteristics of post-mining regions. Vulnerability is assessed through an indicator-based approach, ensuring that both social and physical aspects are systematically evaluated.

Framework and Categorization

The VI is calculated using a set of predefined indicators that capture key social and physical vulnerabilities. These indicators are grouped into four categories:

1. Socioeconomic Status: Includes indicators (10 indicators see below) that reflect the economic and demographic profile of the area.
2. Household Composition: Considers the vulnerability associated with the population's age distribution.
3. Environment: Evaluates the urban and agricultural environment.
4. Building and Transportation: Focuses on the characteristics of infrastructure and traffic.

The indicators used for this process are:

1. *Below poverty:* Represents the proportion of the population living below the poverty line. Areas with high poverty rates are more vulnerable due to limited resources for hazard mitigation and recovery.
2. *Gross Domestic Product (GDP) per person:* Reflects the economic health of the region, with lower GDP indicating reduced resilience to hazards; expressed in monetary terms.
3. *Population under 17 and over 65 years old:* Highlights the demographic segments more vulnerable to hazards due to dependency or mobility challenges, expressed in percentage.
4. *Population density (people/km^2):* Assesses the concentration of people in a given area, with higher densities potentially exacerbating the impacts of hazards.
5. *Settlement area:* Measures the extent of inhabited regions, indicating the potential exposure to hazards; expressed in percentage.

6. *Urban and agricultural areas:* Differentiates land use, as urban and agricultural areas are impacted differently by hazards; expressed in percentage.
7. *Age of buildings:* Older buildings are generally more vulnerable to structural damage during hazard events.
8. *Material of buildings:* Evaluates the construction materials, with certain materials offering better resistance to specific hazards.
9. *Geometry of Buildings:* Considers the complexity of building designs, as irregular geometries may be more susceptible to damage.
10. *Traffic Area:* Reflects the transportation network's vulnerability, which is critical for emergency response and evacuation; expressed in percentage.

<u>Calculation Process</u>

The VI calculation follows these steps:

1. *Indicator value assessment:* Each indicator's value (for the 10 indicators mentioned above) is determined based on European, national, or local standards. These values are scaled into a nine-point scale, where the lowest part of the range is assigned a value of 1, and the highest part is assigned a value of 9. For example, if an indicator value falls within the fifth sub-range, it is assigned a score of 5.
2. *Weight assignment:* Each group (socioeconomic status, household composition, environment, and building and transportation) is weighted manually by the end-user via the Decision Support System (DSS). These weights reflect the relative importance of each group in the specific case study. The sum of the weights assigned to all groups must equal one to ensure a balanced contribution to the overall VI calculation.
3. *Group score calculation:* The average of the indicator scores within each group is calculated and multiplied by the assigned weight for that group.
4. *Aggregation of group scores:* The weighted scores of all groups are summed to obtain the overall VI for the study area.

<u>Expected Output</u>

The final VI reflects the combined social and physical vulnerabilities in the study area, providing a key input for assessing multi-risk scenarios in subsequent steps. This value enables decision-makers to prioritize mitigation measures and enhance resilience in the most vulnerable areas. Figure 5 illustrating this process will be provided, showing the flow from individual indicators to the final VI calculation. This figure clarifies the relationship between indicator values, group weights, and the overall vulnerability index calculation.

Socioeconomic status	Household composition	Environment	Buildings and transportation
Below poverty (v_1)	Population under 17 y.o. and over 65 y.o. (v_3)	Settlement Area (v_5)	Age of building (v_7) Material of building (v_8)
Gross Domestic Product or GDP per person in the area (v_2)	Population density (people/ km^2) (v_4)	Urban and agricultural areas (v_6)	Geometry (v_9) Traffic area (v_{10})

$$\text{Avg.}(v_1, v_2) \times w_1 + \text{Avg.}(v_3, v_4) \times w_2 + \text{Avg.}(v_5, v_6) \times w_3 + \text{Avg.}(v_7, v_8, v_9, v_{10}) \times w_4 = \text{VI}$$

Figure 5: Framework of Vulnerability Index (VI) calculation

The structured approach of Step 5 ensures that the multi-hazard risk assessment incorporates a robust understanding of vulnerabilities, tailored to the specific characteristics of post-mining areas.

Step 6: Elements at risk (EAR)

The Elements At Risk (EAR) represent the components within an area that are exposed to multi-hazard conditions and are likely to be affected. These elements are critical to this methodology as they provide the quantitative dimension required for assessing the overall multi-risk value. EAR are categorized into four main groups:

1. Population: Includes potential injuries and fatalities resulting from multi-hazard events.
2. Environment: Covers the impact on natural resources, such as soil and water pollution, due to hazardous interactions.
3. Infrastructure: Encompasses buildings, transportation networks, and equipment that may suffer structural or functional damage.
4. Economy: Includes economic assets such as industries, businesses, and agricultural lands that could face financial losses.

This step utilizes Geographic Information Systems (GIS), evaluated in WP4, to spatially identify and map the EAR within the study area. The GIS framework enables the integration of hazard exposure data with the location and characteristics of vulnerable elements, providing a spatial overview of potential impacts. The identified elements are then processed through the Decision Support System (DSS) (evaluated in WP3). For quantification, monetary terms are used to assign values to each EAR, providing a standardized measure of potential losses. End-users can define these values based on local or regional standards and may use euros or other currencies, as supported by the DSS. This flexibility ensures the methodology's adaptability to various regional contexts and enhances its practical application. The output of this step is the identified EAR for each category, their spatial distribution, and their quantified values. This structured approach allows for a detailed understanding of what is at stake in multi-hazard scenarios and forms the basis for subsequent risk calculations.

Expected Output

The expected output of step 6 is a comprehensive list of elements impacted by multi-hazard conditions in each study area, along with their monetary valuation based on national standards.

Step 7: Multi-risk value (MRV)

The Multi-Risk Value (MRV) represents the final output of the multi-hazard risk assessment methodology, providing a comprehensive measure of the risk associated with each multi-hazard scenario. The MRV integrates three critical components: the Multi-Hazard Index (MHI)**,** the Vulnerability Index (VI)**,** and the quantified Elements at Risk (EAR)**.** This combination captures the intensity of hazards interactions, the vulnerability of the affected area, and the economic value of exposed elements, resulting in an outcome expressed in monetary terms.

The MRV for each multi-hazard scenario is calculated using the formula:

$$MRV = MHI \times VI \times EAR \text{ (monetary value)}$$

Since the MHI and VI are indices, the MRV translates the combined hazard and vulnerability conditions into financial implications, aiding in the prioritization and management of risks.

Application and Representation

For each identified scenario, the MRV is calculated by applying the above formula. The results can be represented visually using 2D or 3D diagrams to facilitate interpretation and decision-making:

2D Diagram

- The vertical axis represents the product of the MHI and VI (see Figure 6).
- The horizontal axis represents the monetary value of the EAR (see Figure 6).

This format provides a straightforward comparison of the overall risk level for each scenario.

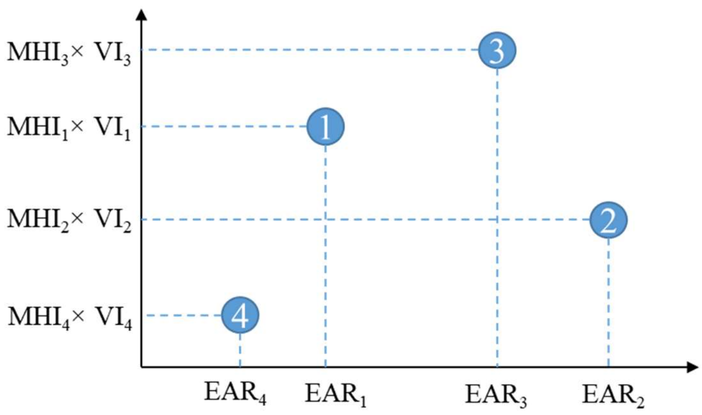

Figure 6: Illustration of MRV for each multi-hazard scenario in 2D diagram

3D Diagram

- The left and right vertical axes represent the MHI and VI, respectively (see Figure 7).
- The horizontal axis depicts the monetary value of the EAR (see Figure 7).

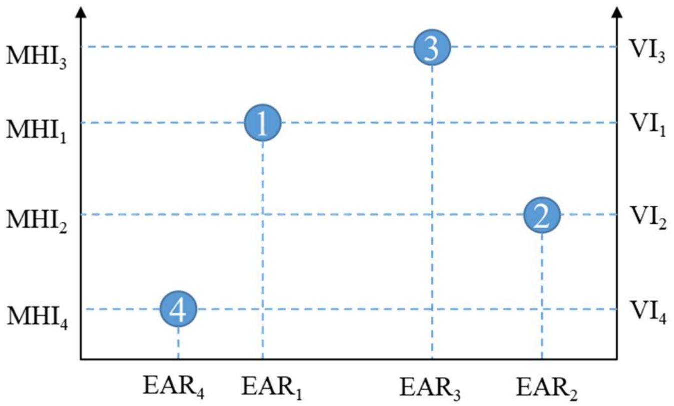

Figure 7: Illustration of MRV for each multi-hazard scenario in 3D diagram

This representation allows for a more detailed visualization of the interactions between the three components.

<u>Evaluation of MRV</u>

The assessment of the calculated MRVs is based on socio-economic criteria and national standards. This evaluation determines whether the identified multi-risk levels are acceptable or require mitigation measures. These thresholds depend on regional or national policies, economic conditions, and societal resilience to potential losses.

<u>Expected Output and Importance</u>

The final output of this step is a diagram summarizing the MRVs for all multi-hazard scenarios, enabling stakeholders to compare and prioritize scenarios based on their financial and socio-economic impacts. The MRV provides a practical, actionable metric for decision-makers to allocate resources effectively and enhance resilience in post-mining areas by quantifying risk in monetary terms.

5 Tools and resources

This section outlines the tools, templates, and resources required to implement the multi-hazard risk assessment methodology effectively. These elements ensure that end-users can apply the methodology consistently and achieve accurate, actionable outcomes.

5.1 Software/Equipment requirements

Users can employ any spreadsheet-compatible tool for intermediate calculations or data management. These tools provide the flexibility needed to support the methodology's requirements at various stages. Spreadsheet tools enable:

- Data entry and organization: Recording initial hazard intensities, interactions, and vulnerability indicators.
- Calculations and analysis: Automating the derivation of adjusted intensities, multi-hazard indices, and multi-risk values using built-in formulas and custom functions.
- Visualization: Creating 2D and 3D diagrams for illustrating multi-risk values and comparing scenarios.

One such tool is the Microsoft Excel, a widely available software that offers the computational and organizational capabilities necessary to implement each step of the methodology effectively.

5.2 Templates and data formats

To standardize and simplify the implementation process, the following templates and data formats are provided:

Excel templates: Pre-configured spreadsheets tailored to each step of the process, including:
Hazard intensity inputs (Step 1).
Interaction matrix setup (Step 2).
Scenario documentation and adjusted intensity calculations (Steps 3–4).
Vulnerability index weighting and indicator scoring (Step 5).
Elements at risk (Step 6).
Final multi-risk value computation and visualization (Step 7).

Data formats: Input data should follow predefined formats, such as numeric scales for hazard intensities and vulnerability indicators to ensure compatibility with templates and automated calculations.

- Input data for hazards (e.g., hazard maps, governmental reports, and expert evaluations) should be entered in numeric form, typically on a scale from 1 to 3.
- Indicators for vulnerability assessment should follow the nine-point scale provided within the deliverable, and their values should be derived based on European, national, or local standards.
- Outputs such as multi-hazard indices and multi-risk values are stored in tabular and chart formats for easy reporting and interpretation.

These templates and data formats reduce complexity and minimize errors, enabling end-users to focus on decision-making rather than data processing.

5.3 Additional resources

To support users in applying the methodology, the following resources are recommended:

Supporting documentation:
- Deliverable 2.1 from the POMHAZ project provides the necessary theoretical background and practical guidelines for hazard susceptibility.
- Deliverable 2.3 from the POMHAZ project referenced for adjusted intensity principles.

Web-based resources:
- Supporting documentation for users unfamiliar with advanced spreadsheet functions.

Decision Support System (DSS): Developed in WP3, a customized DSS is being developed as part of the project, allowing users to perform calculations, apply weights, and quantify elements at risk more efficiently.

The DSS incorporates a quantitative scale for interactions and facilitates comparisons among multi-hazard scenarios. It integrates data from hazards with different timeframes and applies criteria for ranking and prioritizing risks. It accounts for mitigation techniques and provides a robust tool for land management and spatial planning in post-mining areas.

The DSS interface will streamline the implementation process and provide options for visualizing outputs in various formats, including tables, charts, and maps.

Geographic Information System (GIS): The GIS-DSS system developed in WP4 combines hazard mapping with decision-making tools. Multi-hazard maps illustrate the interactions and consequences of hazards and serve as a critical resource for stakeholder engagement and decision-making. The GIS interface allows users to assess hazard boundaries, identify risks, and recommend mitigation measures.

Supporting Literature: The following list of supporting literature represents the minimum essential references for understanding and applying the multi-hazard risk assessment methodology outlined in this deliverable. These sources provide the theoretical foundation, methodological insights, and practical guidance necessary to implement the approach effectively. While additional literature may further enhance comprehension, this selection has been curated to cover the key aspects of the methodology. For practitioners and researchers, these references serve as a starting point to gain the knowledge required for adapting the methodology to specific post-mining contexts.

- Multi-hazard analysis: Liu, Han et al. (2021).
- Decision Support Systems for multi-hazards in coal mines: Komendantova, Mrzyglocki et al. (2014), Newman, Maier et al. (2017).
- Vulnerability Index: Cutter, Boruff et al. (2012).

These tools and resources ensure that the methodology is accessible, practical, and adaptable to a wide range of post-mining case studies. Combined with the templates and guidelines, they provide a comprehensive toolkit for addressing multi-hazard risks effectively.

6 Essential points for effective application

While the multi-hazard risk assessment provides a robust framework for assessing and managing risks in post-mining areas, there are certain points that require attention to ensure accurate application and interpretation of results.

Comparability of multi-hazard indices: A certain point of the methodology is that multi-hazard indices are not inherently comparable across scenarios with differing numbers of hazards. The summation of adjusted intensities for each scenario inherently results in scenarios with more hazards, as they will tend to have higher MHI values. This does not necessarily indicate that such scenarios are more catastrophic, as the nature and scale of hazards vary.

Recommendations / Proposed Solutions:

- Comparison within groups: Restrict comparisons to scenarios with the same number of hazards. While this ensures valid comparisons, it also parameters the flexibility and usability of the methodology.
- Normalization: Develop normalized MHI values by creating upper and lower limits for each group of scenarios with the same number of hazards.
    Lower Limit: Based on the lowest hazard intensity interacting at the lowest level with another hazard.
    Upper Limit: Based on the highest hazard intensity interacting at the highest level with another hazard.

  Normalization ensures comparability across scenarios while preserving methodological flexibility.

Data availability and quality: The accuracy of the methodology heavily depends on the availability and quality of input data, including:

Hazard intensities**:** These are obtained from Step 1 of the methodology, and inaccuracies or gaps in hazard susceptibility mapping may propagate through the process.

Vulnerability indicators**:** Social and physical vulnerability indicators must be well-defined and quantified using reliable sources. Inconsistent or outdated data could skew the vulnerability index.

Elements at risk**:** Quantifying elements at risk in monetary terms requires accurate data on infrastructure, the environment, population, and economic activities, which may not always be available, especially in regions with limited resources or inconsistent data collection practices.

Linear interaction models**:** The adjusted intensity calculation assumes that interactions between hazards can be expressed using qualitative and quantitative multipliers. This approach may not fully capture the complexity of hazards' interrelationships, particularly for cascading or compounding hazards.

End-user subjectivity: The methodology allows end-users to manually input hazard interaction level, weights for vulnerability indicators and quantify elements at risk. While this flexibility is a strength, it also introduces subjectivity, as results may vary depending on the expertise, priorities, or biases of the end-user.

By acknowledging these certain points, the methodology can be continuously refined, ensuring its relevance and adaptability for diverse applications in post-mining areas. To address these points in future work, we recommend exploring quantitative approaches for hazard interactions. Although these methods demand extensive data and computational resources, they offer the potential to provide deeper insights into the dynamics of multi-hazard interactions. In the meantime, semi-quantitative methodologies continue to serve as valuable approach for assessing multi-hazard risks in contexts with limited data availability.

7 Case studies/examples

Case studies demonstrate the methodology's practical application, illustrating how hazards are identified, quantified, and how their interactions are assessed. The insights gained through these analyses provide a valuable framework for informed decision-making and effective risk management in post-mining areas. Results in WP5, particularly Deliverable D5.3, implements this methodology within the GIS and DSS framework to enhance hazard mapping and scenario development for European post-mining areas.

The multi-hazard risk methodology outlined in this deliverable is applied to several case studies across different regions, providing a comprehensive test of its effectiveness in diverse post-mining areas. These case studies, located in Europe, serve as representative examples of the practical application of the methodology. The areas selected for study feature a range of geological, hydrological, and socio-economic conditions, offering valuable insights into the complexities of hazard interactions in post-mining areas. For each case study, critical hazards are identified based on local conditions, historical mining activities, and potential interactions. A detailed hazard assessment is conducted to determine the intensity and interrelationships of these hazards, forming the foundation for applying the methodology's steps and tools. These case studies enable the refinement of the methodology and provide insights into its adaptability to various post-mining scenarios.

Data collection forms the cornerstone of the hazard intensity determination. Historical records events, along with national hazard maps and governmental reports, provide the basis for evaluating each hazard's predisposition and potential impact. A consistent three-point intensity scale (1–3) is employed to ensure comparability across hazards.

8 Conclusions

The methodology presented in this deliverable offers a robust and systematic framework for assessing multi-hazard risks in post-mining areas, addressing the complex interactions among hazards and their impacts on socio-economic and environmental stability. By integrating a semi-quantitative approach with flexible tools, the methodology bridges the gap between theoretical frameworks and practical applications, enabling stakeholders to manage and mitigate risks effectively.

A key achievement of this deliverable is the development of a structured seven-step process that guides users from hazard identification and susceptibility analysis to the final assessment of multi-risk values. This process incorporates innovative techniques such as interaction matrices, adjusted intensity principles, and indicator-based vulnerability assessments, ensuring that the methodology is both adaptable and comprehensive. Additionally, the inclusion of templates, resources, and software requirements facilitates consistent implementation across diverse post-mining contexts.

Despite its strengths, the methodology acknowledges limitations, including data quality constraints, challenges in standardizing hazard interaction levels, and the non-comparability of Multi-Hazard Indices (MHI) across scenarios with differing hazard counts. Proposed solutions, such as normalization techniques, enhance the methodology's robustness and applicability, ensuring meaningful comparisons of risk levels. These refinements highlight the project's commitment to addressing methodological challenges while fostering continuous improvement.

The inclusion of case studies demonstrates the methodology's real case study applicability and underscores its relevance to European coal regions transitioning toward sustainable development. By providing a detailed example, the deliverable illustrates how the methodology can inform decision-making, prioritize mitigation strategies, and enhance resilience in communities affected by post-mining hazards.

Looking ahead, the implementation of the methodology in future work packages will further validate its effectiveness and adaptability. The continued development of tools such as the DSS and GIS, as outlined in WP3 and WP4, will enhance its capacity to address the unique challenges of post-mining areas, supporting stakeholders in achieving long-term socio-economic and environmental stability.

This deliverable represents a significant step forward in multi-hazard risk assessment for post-mining areas, contributing to the broader objectives of the POMHAZ project. It provides stakeholders the knowledge, tools, and processes necessary to navigate the complexities of post-mining risk management, aligning with the principles of decarbonization and just transition.

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10 Appendices

List of appendices:

- Appendix A: Identified hazards associated with post-mining areas, as outlined in the project's database in WP2
- Appendix B: Terminology

Appendix A

This appendix presents the identified hazards associated with post-mining areas, as outlined in the project's database in WP2 (Table A1). The hazards listed here are derived from column B of the Excel sheet titled "Database" in Deliverable 2.1 and were compiled based on feedback and contributions from all project partners. This comprehensive list serves as a key reference for Step 1 of the multi-hazard risk assessment methodology, guiding users in selecting hazards relevant to their specific case studies.

Table A1: Identified hazards in post-mining areas from Deliverable 2.1.

Name of hazard
Subsidence
Settlement
Slope movement (slope stability) - (Generalized scale- level of whole excavation)
Slope movement (slope stability) - (Local scale- level of bench)
Rock falls
Induced seismicity
Sinkhole
Crevice
Environmental water pollution
Environmental pollution from spoils
Environmental pollution from tailings dams
Hydrological disturbances, mining induced floods
Hydrological disturbances, mining induced floods
Hydrological disturbances, mining induced floods
Ionizing radiation emissions
Gas emissions linked to mining
Combustion and overheating of mine waste

Appendix B

This part is utilized for understanding the terminology applied throughout the guidelines of the methodology in the current deliverable. Hazard and risk analysis extend across numerous scientific fields, each offering various definitions for fundamental terms. In the context of multi-hazard risk analysis, clarity is crucial when using general terms, as their meanings can differ depending on disciplinary and methodological perspectives. In recent years, multi-hazard analysis has experienced substantial growth, leading to diverse definitions with subtle distinctions. Specific definitions for multi-hazard concepts are still emerging, and a consistent set of terms has yet to be universally adopted across disciplines. Consequently, general terms such as 'multi-hazard,' 'multi-risk,' and 'vulnerability' may hold different implications across applications. To ensure clarity and avoid misinterpretation, the definitions selected in this section represent interpretations that are widely accepted and referenced in the literature, while aligning closely with the objectives of multi-hazard risk assessment in post-mining contexts.

Table B1 below presents key terms as they are used within this methodology. Each term's definition is backed by established literature, ensuring a well-rounded and recognized foundation for these concepts. This shared terminology is particularly important for facilitating communication across disciplinary boundaries and for supporting consistent application of multi-hazard risk analysis methodologies. This section not only sets the framework for understanding the analysis in this deliverable, but also aids end-users in adapting these concepts to their own post-mining multi-hazard risk assessments by clearly defining each term.

Table B1: Definitions of key terms and concepts relevant to multi-hazard risk assessment in post-mining areas.

Term	Definition	Reference
Post-mining	Regions that were subjected previously to mining activities and have since been abandoned or repurposed following the cessation of mining operations. These areas often face significant challenges due to the environmental degradation and infrastructural changes caused by mining.	(E.C. 2012)
Hazard	A dangerous phenomenon, substance, human activity or combination that may cause loss of life, injury, or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.	United Nations International Strategy for Disaster Reduction (UN-ISDR) (2009), (Field, Barros et al. 2012)
Multi-hazard	It refers to: - different hazardous events threatening the same exposed elements (with or without temporal coincidence); - hazardous events occurring at the same time or shortly following each other (cascade effects). It refers to the totality of relevant hazards in a defined administrative area	Kappes, Keiler et al. (2010), Kappes (2011)
Cascading effect	It refers to a sequence of events where one hazard triggers subsequent hazards, leading to a chain reaction of impacts. This phenomenon is characterized by the interplay and amplification of multiple hazards over time and space, resulting in compounded risks and vulnerabilities.	Gill and Malamud (2014), Gill and Malamud (2016)
Vulnerability	The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.	United Nations International Strategy for Disaster Reduction (UN-ISDR) (2009), Field, Barros et al. (2012)
Physical vulnerability	It refers to the susceptibility of buildings and infrastructure to damage from different types of hazards. It is assessed by evaluating various indicators related to the structural properties and environmental conditions of the built environment.	Kappes, Papathoma-Koehle et al. (2012), Papathoma-Köhle, Gems et al. (2017), Singh, Kanungo et al. (2019)
Social vulnerability	It refers to the susceptibility of communities to be adversely impacted by hazards and public health emergencies. It encompasses various socioeconomic and demographic factors that affect a community's resilience and ability to recover from such events.	Flanagan, Gregory et al. (2011), Cutter, Boruff et al. (2012)
Exposure	The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas.	UNDRR (2015)
Elements at risk	People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses.	United Nations International Strategy for Disaster Reduction (UN-ISDR) (2009), Field, Barros et al. (2012)
Multi-hazard risk	It refers to the risk arising from multiple hazards.	Kappes, Keiler et al. (2012)
Multi-risk	It is related to multiple risks such as economic, ecological, social, etc. It determines the whole risk from several hazards, taking into account possible hazards and vulnerability interactions entailing both a multi-hazard and multi-vulnerability perspective.	Carpignano, Golia et al. (2009), Kappes, Keiler et al. (2012), Marzocchi, Garcia-Aristizabal et al. (2012)

What is PoMHaz?

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

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

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

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