Mine Closure 2024 – AB Fourie, M Tibbett & G Boggs (eds)

doi:10.36487/ACG_repo/2415_86

Multi-hazard index for assessing the interaction of post-mining hazards

Marwan Al Heib [a,*], Nathalie Velly [a]

[a] *Ineris, France*

Abstract

The number of abandoned coal mines is continuously increasing in Europe due to the energy transition. Therefore, post-mining risk assessment and associated management remain crucial for mining authorities, policymakers and planners. The paper presents a new approach to adjusting the level of the single hazards considering the interaction between the post-mining hazards. The value of the adjusted hazard is the product of the level of the initial hazard and the level of interaction of this hazard with another hazard. Based on the number and level of the interaction between hazards, the multi-hazard index (MHI) is a score allowing different regions, sectors, etc. to be compared. The multi-hazard index approach can be used for territories presenting multiple hazards to target areas in which the number of interactions between hazards is significant, considering the level of hazard of each expected phenomenon. It thus makes it possible to prioritise sectors for overall hazard management.

Keywords*: multi-hazards, post-mine, interaction, matrix, index, methodology*

1 Introduction

Mined land, after the cessation of mining activities, is generally affected by several post-mining hazards (Aldridge et al. 2016; Cammand Girard-Dwyer 2000; Mutke & Bukowski 2011) (Figure 1). The risk and hazard assessment studies have often focused on the detailed examination of a single hazard phenomenon (ISRM 2008; Ineris 2018). Chang et al. (2022) studied a large mining area (several square km) where the instability of artificial slopes is increased due to rainfall infiltration. This study did not show the potential interaction between hazards. In an abandoned mining area, several mining hazards can potentially interact (Lazar et al. 2015; John 2021). For example, Digges La Touche et al. (2018) discussed the development of a sinkhole due to mine flooding. The interaction between flooding and ground movement is frequently observed (Ma et al. 2022). Expert feedback must be used to establish the interaction between mining-mining hazards, mining-natural hazards and mining-technological hazards.

Thus, the assessment of one mining hazard can be unmanageable when multiple hazard types must be considered (Roumpos & Pavloudakis 2019). However, a multi-hazard approach in a post-mining context is not obvious: the available data for the different single hazards may refer to different spatial scales. The comparisons, rankings and aggregations can be difficult, and different specialised organisations and experts need to collaborate to assess the interaction between different post-mining hazards. On the other hand, the multi-hazard/multi-risk analysis around abandoned mines can present several advantages, which are summarised as follows:

- better assessment of the intensities and predisposition of hazards around mine closures through scenarios associated with their interactions
- better consideration of the vulnerability of the challenges of a territory exposed to several hazards
- a more comprehensive consideration of interactions between mining hazards

[*] Corresponding author. Email address: marwan.alheib@ineris.fr

- a global and integrated view of the risk which leads to a better preservation of the general interests identified around abandoned mines
- improvement in the resilience capacity and sustainability of the territories
- improvement of the communication plan and the decision-making
- selection of the most useful mitigation solution and risk management.

This paper presents the development of a methodology of multi-hazard analysis of abandoned mines instead of analysing single hazards separately. The overall objective is to improve the methodological knowledge for practical implementation of multi-hazards analyses, at the scale of a mining basin, in correlation with the main kind of post-mining hazards. The work aims to test and adapt the developed methodology by considering the different risks that affect mining regions. The European Commission (2010) and United Nations Office for Disaster Risk Reduction (UNDRR 2020) define the hazard and multi-hazard assessment related to natural phenomena. In this paper we will address the post-mining hazards.

Figure 1 An overview of the hazards associated with mining activities (Rebello et al. 2021)

2 Hazard categories in mining areas

The methodology of multi-hazard assessment should consider the interactions between hazards (Eshrati et al. 2015). The interaction between the hazards depends on the knowledge of intensity and predisposition of the site for each individual hazard. The Figure 2 presents the main steps, five in total, to carry out the multi-hazard assessment of post-mining hazards. After the identification of the single mining hazards, the main step is the identification of the interaction between the mining hazards. The first step is dedicated to the description of mining hazards and natural hazards. The possible interaction between the hazards is generated according to:

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

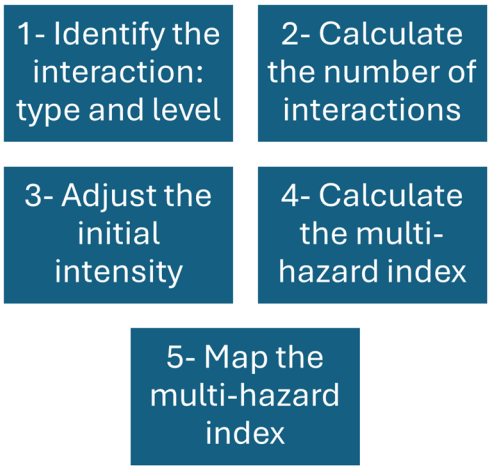

Figure 2 Suggested methodology for assessing the multi-hazard interaction in post-mining land

3 Mining hazards interactions

The methods for assessing mining hazards are different from those used for natural and technological hazards (Spanidis et al. 2019). A mining hazard is qualified according to its intensity and the predisposition of the mining site because there is no probability of occurrence. Regardless of what type of mining-induced event is anticipated, because of the complexity of mechanisms, the heterogeneous nature of the natural surroundings, the incompleteness of the available information and the fact that numerous disturbances, after-effects or nuisances are not repetitive, it is generally impossible to reason in terms of a probabilistic quantitative approach (Ineris 2018). Therefore, we use a qualitative classification that characterises a site's predisposition to being affected by a given phenomenon. This is the concept that will be used in this document. Three intensity classes are considered (limited, moderate and high) and three predisposition classes (not very sensitive, sensitive and very sensitive). These classes allow the hazards to be assessed; either by prioritising the damage or potential nuisances according to the nature of the phenomena. The predisposition replaces the likelihood used in classical hazard and risk analysis. In mining risk assessment, the mining hazard = intensity × predisposition.

There is not yet a methodological framework of reference for the assessment of multi-hazards for post-mining sites. However, two tools are generally used for assessing the interaction between the potential hazards (Gill & Malamud 2014; Garcia-Aristizabal et al. 2015): the matrix of interactions and the diagram of interaction (Figure 3). The rows of the matrix correspond to the primary hazards, which means that the hazards will be the first hazard that can occur on the mining site and can trigger a secondary hazard among the settlers. This means that each primary hazard can trigger one or more hazards immediately or later. The diagram of the interactions should be built for each hazard. The level of interaction between hazards is estimated from the factors determining their intensity on the one hand and their probability of occurrence on the other hand. Based on the approach presented by Liu et al. (2021) and feedback from the evaluation and assessment of the mining hazards, we consider three levels of potential interactions:

- low or no interaction — no potential for interaction (temporal and spatial) of the existing identified hazards
  - there is no modification of the level of the hazard's intensity
- medium — between the existing hazards (e.g. the interaction between subsidence and flooding)

  - the initial hazard intensity will be increased, at least by one level
- high — between the existing hazards (e.g. the interaction between the sinkhole and flooding)
  - the initial hazard intensity will be increased, at least by one level or two levels, depending on the initial intensity levels of the interacted hazard.

For instance, six main mining hazards are identified (ground movement, flooding, self-heating, gas, radioactivity and pollution), thus, the interaction matrix is composed of 6 × 6 mining hazards. In this case, theoretically, 36 potential interactions corresponding to the boxes of the interaction matrix should be studied (Figure 3). Based on expert feedback, only 13 interactions were judged as possible due to the predisposing factors: seven high-level, three medium (moderate) level and three low level interactions. There are as many as 21 post-mining hazards, and each hazard can be divided by sub-hazards (Al Heib et al. 2023).

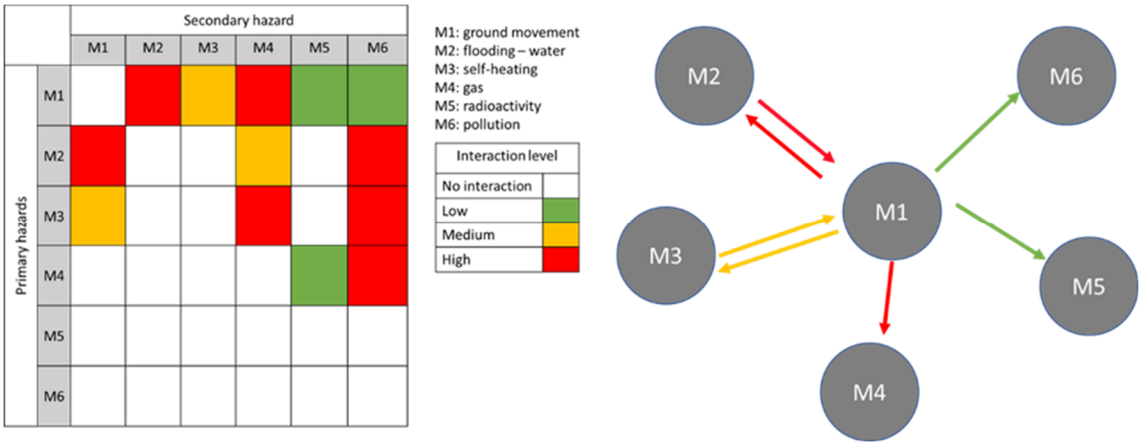

Figure 3 The matrix of interactions and the diagram of interaction between the six main mining hazards (M1 to M6)

Ground movement can interact with four mining hazards to trigger other mining hazards as follows:

- flooding (M1-M2) — the ground movement occurrence (e.g. gallery collapse, shaft collapse, subsidence, etc.) can damage the water system of the mine, tailings dam, etc. Consequentially, the ground movement hazard can trigger the flooding of an abandoned mine. This interaction can be a domino interaction or an aggravation of the factor of the flooding hazard. The level of the interaction can be considered as high (red)
- self-heating (M1-M3) — the ground movement occurrence (landslide, crevasse, etc.) can increase air penetration through the coal dumps, which include a high quantity of coal with a self-heating predisposition. Consequentially, the ground movement hazard can trigger the self-heating of an abandoned coal mine. This interaction corresponds to an aggravation of the self-heating hazard. The level of the interaction can be considered as moderate (orange)
- gas (M1-M4) — the ground movement occurrence (general collapse, sinkhole, crevasse, etc.) can increase the permeability of the terrain and gas hazard predisposition, mainly the gas flow. Consequentially, the ground movement hazard can trigger the gas hazard of an abandoned coal mine. This interaction corresponds to an aggravation of the gas hazard. The level of the interaction can be considered as high (red)
- radioactivity (M1-M5/M6) — the ground movement occurrence (general collapse, sinkhole, crevasse, landslide, etc.) can increase the permeability of the terrain, and the pollution and radioactivity predisposition. Additionally, the ground movement can generate particles whose deposits can pollute soil, air and water. Consequentially, the ground movement hazard can trigger or facilitate the pollutant transfers. This interaction corresponds to a slight aggravation of the radioactivity-pollution hazard. The level of the interaction can be considered as low (green).

In summary, for ground movement interactions there are two high (red), one medium (orange) and one low (green) levels. The same analysis was done for the five mining hazards. Notice that the hazard matrix is not symmetric.

4 Mapping the multi-hazard result

The main purpose of mapping the multi-hazard result is to gather in one map the different hazard-related information for a study area to convey a composite picture of the hazards of varying magnitude, frequency and area of effect (Organization of American States [OAS] 1991). Two approaches can be considered for the calculation of the adjusted hazard level and the multi-hazard index, and these will be presented and discussed. The first approach consists of the adjustment of the initial hazard level (intensity) based on the level of the interaction. Table 1 presents an example of the adjustment of the level of the hazard due to their interaction. The initial hazard level (intensity) is upgraded by at least one level. The new intensity can be mapped using the classical hazard mapping methods.

Table 1 Example of adjusted hazard level considering the multi-hazard analysis and hazard interaction

Initial hazard level	Interaction level	Adjusted hazard level
Low/Medium/High	Low/no interaction	Low/medium/high
Low	Medium	Medium
Medium		High
High		High
Low	High	Medium
Medium		High
High		Very high

The second approach consists of a calculation of a multi-hazard index (MHI). The value of the MHI can be calculated after the adjustment of each single hazard as follows:

$$MHI = \sum_1^n H_{ad-i} \quad (1)$$

where:

N = number of single hazards identified on the studied site

H_{ad-i} = adjusted intensity of the single hazard (Hi).

The calculation of MHI needs to convert the level of the hazard by a number; for instance, 1, 2 and 3 corresponding to low, medium and high.

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

- no interaction or low interaction, no adjustment is necessary
- moderate interaction level, the adjustment coefficient is equal to two
- high interaction level (cascading interaction), the adjustment coefficient is equal to three.

The Table 2 represents the adopted coefficient following the level of the initial mining hazard intensity and the level of the interaction. Those coefficients can be modified for a specific context based on local expert opinion. The adjusted hazard level varies from one to nine. The justification of this choice is based on the consequences of the impact of the natural hazards.

Table 2 Adjusted coefficients of the initial hazards due to their interactions with mining or natural hazards

Initial mining hazard level		Interaction level		Adjusted hazard level		
Qualitative	Quantitative	Qualitative	Quantitative	Quantitative		
Low	1	Low	1	1	2	3
Moderate	2	Moderate	2	2	4	6
Severe	3	High	3	3	6	9

We will consider a virtual case study corresponding to one mine presenting two hazards (H1: sinkhole and H2: flooding) but with two sectors to illustrate the calculation of the multi-hazard intensity (MHI):

$$MHI = Had1 + Had2 \tag{2}$$

where Had1 and Had2 are the adjusted hazard values for hazard one (H1) and hazard 2 (H2).

Based on the interaction matrix and diagram, the interaction level between the two mining hazards can be considered as severe. Thus, the coefficient of interaction is equal to three.

- First sector
  - H1 with a moderate intensity level (H1 = 2)
  - H2 with a low intensity level (H2 = 1)
  - The adjusted intensities for H1 and H2 are: Had1 = 2 × 3 = 6 and Had2 = 1 × 3 = 3
  - Finally, the MHI (1, 2) = 6 + 3 = 9
- Second sector
  - H1 with a severe intensity level (H1 = 3)
  - H2 with a high intensity level (H2 = 3)
  - The adjusted intensities for H1 and H2 are: Had1 = 3 × 3 = 9 and Had2 = 3 × 3 = 9
  - Finally, the MHI (1, 2) = 9 + 9 = 18.

The comparison highlights the difference between the two sites. The MHI values can be used as a unique number to represent the interaction impact on the two hazards: sinkhole and flooding. The calculation can be carried out for hazards with different levels of interaction.

5 Application of the methodology on a case study

The case study involves a former lignite coal mine in the south of France (Figure 4). The depth of the mining works is between 0 and 800 m, with several shallow mines (10–140 m). The risk assessment studies carried out after the shutdown of mining activities identify several hazards which can be grouped as follows:

- mining — ground movements (subsidence and landslide), flooding, self-heating
- natural — wildfire, flood, natural seismicity, land movements (subsidence and collapses associated with underground cavities, landslide, rock and boulder falls)
- technological — transport of dangerous goods

- ground movement — the four assessed are localised collapse, subsidence, landslide and settlement
- localised collapse (sinkhole) — the hazard level is between 'low' and 'medium'
- subsidence — the hazard level is between 'medium brittle subsidence' and 'weak flexible subsidence'
- landslide — the hazard of the landslide of the slag heaps is of 'low' level with an intensity between 'very limited' and 'limited', and the hazard level is low
- settlement — the hazard is localised to the right of each slag heap and was qualified as not very sensitive with a limited intensity, so the hazard level is low.

Figure 4 Localisation of the closed lignite coal mine (France)

The self-heating hazard of the slag heaps is 'low to medium' level and it is only relevant to outcrop zones where mining works have been shown (or, are supposed) to catalyse and worsen this phenomenon. This hazard could trigger a wildfire hazard.

The flood hazard relating to the modification of the mine water regime was assessed as 'low', and the 'brutal' flood hazard was assessed as 'weak to strong'. This hazard relates to the significant inflow of water into the drainage and water collection systems of the most sensitive slag heaps. The hazard level is low.

Based on the hazard assessment and the former mining land, we divided it to three homogeneous sectors: S1, with six mining hazards, and S2 and S3 with three mining hazards each. Table 3 presents the different identified mining hazards as well as the intensity level. The mining hazards are mostly low to medium level. Table 4 clearly shows the existence of multi-hazards in the mining area. Thus, it is necessary to assess the different mine-mine hazard and mine-natural hazard interactions.

Table 3 Lignite mine — intensity level of post-mining hazards

Sector	S1	S2	S3
Mining hazard/level	6 hazards	3 hazards	3 hazards
Ground movement — sinkhole	1	2	
Ground movement — subsidence	1	2	
Ground movement — landslide	1		1
Ground movement — settlement	1		
Self-heating	1	1	1
Flooding	1		1
Multi-hazard index (MHI)	62	17	14

The matrix of the interaction was built based on the assessment of the factor of each hazard (Table 4). The flooding hazard due to the mining activity can be a trigger of all the mining hazards and the level of interaction is high. The flooding and the water fluctuation can increase the ground movement (sinkhole, subsidence, landslide, settlement) and the self-heating intensity. The main impact of the water is decreasing of the strength parameters and mobilising the faults and discontinuity displacement. Furthermore, the occurrence of the mining hazards (flooding and collapse of the coal mine galleries, subsidence) corresponds to a cascade scenario and thus cascade interaction. The likelihood of a cascade scenario is relatively low, but it is certainly not zero.

Table 4 Lignite mine — multi-hazards interaction matrix and assessment of the level of the interaction: red, high; yellow, medium

	Sinkhole	Subsidence	Landslide	Settlement	Self-heating	Flooding
Sinkhole		3	2	3		3
Subsidence	2		2	3	2	3
Landslide	2	2		2	2	3
Settlement	1	1	1		1	1
Self-heating	1	2	3	1		1
Flooding	3	3	3	3	2	

Based on the multi-hazard interaction matrix (Table 4) and the level of hazards (Table 3) for three sectors (1, 2 and 3), the multi-hazard interaction index was calculated using Equations 1 and 2. Therefore, the value of the MHI presented in Table 3 was calculated based on the level of the interactions and the level of the initial hazards, allowing calculation of the adjusted hazard level. For instance, the sector S1 is characterised by six hazards with a low level (1). The sinkhole hazard interacts with four hazards so the level of interaction is medium and high (2 and 3). Thus, the MHI (sinkhole, low) is equal to 1× (3 + 2 + 3 + 3) = 11, MH (subsidence, low) = 12, etc. The MHI for the six hazards (S1) is 62 = 11 + 12 + 11 + 5 + 8 + 14; the MHI for three hazards (S2) is 17 = 6 + 8 + 3; the MHI for three hazards (S3) is 14 = 5 + 4 + 5. Sector one presents the highest score with MHI equal to 62, while Sectors 2 and 3 have an MHI of 17 and 14, respectively. Notice that the value of MHI expresses the number of hazards, the number of interactions and the level of the interactions. The value of multi-hazard analysis is to highlight the importance of Sector 1, which initially presented six individual hazards with low levels but which, due to their interactions, can magnify their impact and make the risk much higher, thereby increasing the negative social and economic consequences.

6 Conclusion

The assessment of the potential interactions of mining hazards is very important for the management former mining land. This paper presented the development of multi-hazard interactions and assessment in former abandoned mines. A methodology was developed to assess and map the multi-hazards using a multi-hazard index. The multi-hazard analysis improves management of the mined land and assessment of the interaction of mining hazards enables us to anticipate the occurrence of unsuspected events. The multi-hazard index allows comparison between sectors and mines. This methodology consists in the following steps:

- first — identification of the potential post-mining hazards
- second — identification of the potential interaction of hazards
- third — identification of the type and level of interaction
- fourth — calculation of the MHI.

The multi-hazard assessment methodology was applied on a lignite coal mine where six post-mining hazards were identified. The mine was divided into three homogeneous sectors. Sector one presented the highest score with an MHI equal to 62, while Sectors 2 and 3 had an MHI of 17 and 14, respectively. The value of MHI expresses the number of hazards, the number of the interactions and the levels of interactions.

The methodology can be improved to address interactions between post-mining hazards and natural and technological hazards.

Acknowledgement

This work has received funding from the European Union's Research Fund for Coal and Steel under the project POMHAZ grant agreement No 101057326. Financial assistance by the European Commission is much appreciated.

References

Al Heib, MM, Franck, C, Djizanne, H & Degas, M 2023, 'Post-mining multi-hazard assessment for sustainable development', *Sustainability*, vol. 15, no. 10, https:// doi.org/10.3390/su15108139

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*, Institution of Chemical Engineers, Rugby.

Camm, T & Girard-Dwyer, J 2000, *Economic Consequences of Mining Injuries*, National Institute for Occupational Safety and Health, Spokane.

Chang, M, Dou, X, Tang, L & Xu, H 2022, Risk assessment of multi-disaster in mining area of Guizhou, China', *International Journal of Disaster Risk Reduction* vol. 78, https://doi.org/10.1016/j.ijdrr.2022.103128

Eshrati, L, Mahmoudzadeh, A & Taghvaei, M 2015, 'Multi hazards risk assessment, a new methodology', *International Journal of Health and Disaster Management*, vol. 3, no. 2.

European Commission 2010, *Risk Assessment and Mapping Guidelines for Disaster Management*, European Commission, Brussels.

Garcia-Aristizabal, A, Gasparini, P & Uhinga, G 2015, 'Multi-risk assessment as a tool for decision-making', in S Pauleit, A Coly, S Fohlmeister, P Gasparini, G Jørgensen, S Kabisch, WJ Kombe, S Lindley, I Simonis & K Yeshitela (eds), *Urban Vulnerability and Climate Change in Africa, Future Cities 4*, Springer, Cham, pp. 229–258, https://dx.doi.org/10.1007/978-3-319-03982-4_7

Gill, JC & Malamud, BD 2014, 'Reviewing and visualizing the interactions of natural hazards', *Review of Geophysics*, vol. 52, no. 4, pp. 680–722, https://dx.doi.org/10.1002/2013RG000445

Ineris 2018, *Post-Mining Hazard Assessment: Methodological Guide 17-164640-01944A*.

ISRM 2008, *Mine Closure and Post-Mining Management International State-of-the-Art*, International Commission on Mine Closure, International Society for Rock Mechanics, https://www.ineris.fr/sites/ineris.fr/files/contribution/Documents/CDi__mineclosure_29_11_08-ang.pdf

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*, vol. 1, no. 1, pp. 35–58, https://doi.org/10.3390/mining1010004

Digges La Touche, G, Balding, B, Keenan, B & Digges La Touche, S 2018, 'Sinkhole development on mine flooding', in C Wolkersdorfer, A Weber, GTremblay, L Sartz, J Burgess (eds), *Proceedings of the 11th ICARD/ IMWA/ MWD Conference – Risk to Opportunity*, International Mine Water Association, Lakewood, vol. 2, pp. 585–590.

Lazar, M, Nyari, I-M & Faur, FG 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*, vol. 10, no. 3.

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*, vol. 12, no.1, pp. 2544–2560, https://dx.doi.org/10.1080/19475705.2021.1969451

Ma, S, Qiu, H, Yang, D, Wang, J, Zhu, Y, Tang, B, Sun, K & Cao, M 2022, 'Surface multi-hazard effect of underground coal mining', *Landslides*, vol. 20, pp. 39–52, https://dx.doi.org/10.1007/s10346-022-01961-0

Mutke, G & Bukowski, P 2011, 'Diagnosis of some hazards associated closuring of mines In Upper Silesia Coal Basin – Poland', *Proceedings of the 11th International Multidisciplinary Scientific GeoConference of Modern Management of Mine Producing, Geology and Environmental Protection*, International Multidisciplinary Scientific GeoConferences, Sofia, pp. 429–436.

OAS 1991, *Primer on Natural Hazard Management in Integrated Development Planning*, https://www.oas.org/dsd/publications/unit/oea66e/begin.htm#Contents

Rebello, S, Annoopkumar, AN, Aneesh, EM, Sindhu, R, Binod P, Kim, SH & Pandey, A 2021, 'Hazardous minerals mining: challenges and solutions', *Journal of hazardous materials*, vol. 402.

Spanidis, PM, Roumpos, C & Pavloudakis, F 2019, 'A methodology for natural hazards risk management in continuous surface lignite mines', *Proceedings of the 2nd International Conference on Natural Hazards & Infrastructure'*, National Technical University of Athens, Athens.

UNDRR 2020, *Hazard definition and Classification Review*, United Nations, Geneva.