



A framework for assessing hazards related to pit lakes: application on European case studies

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Abstract

The number of abandoned mines is continuously increasing in the world. The sustainable exploitation of these abandoned mines is a top priority globally. Pit lakes created in abandoned mining sites provide benefits and present risks for the mining region. This paper presents a methodology to assess the mining and natural hazards related to pit lakes. The proposed methodology framework is based on well-established and internationally accepted risk management standards and allows the assessment of the long-term stability of pit lakes. Potential ground movements, water pollution, fire hazards are presented, and their impact evaluated based on feedback and international experience. The methodology was applied for 13 European pit lakes created in former European coal and lignite mines. A risk assessment of the Most lake was carried out, using qualitative and a weighted probabilistic approach that considers the overall and the individual effect of identified mining and natural hazards. Results showed that the main potential hazards are the ground movements, slope stability, and flooding.

Keywords Risk · Methodology · Open-pit lake · Qualitative · Probabilistic

Introduction and objectives

Europe has entered the phase of stopping all coal and lignite mines to reduce the impact on the environment (Oei et al. 1995). After the cessation of mining, decreasing the environmental impact is the main challenge for each mining region (Wirth and Lintz 2006; Blanchette and Lund 2016; van Aanhout and Hedley 2009; European Commission 2020). Social, economic, and technical studies are generally carried out to find out the best solution for the environment (Smith and Underwood 2000; McCullough and Lund 2006; Mborah et al. 2016; Schuchova et Lenart 2020; Sakellari et al. 2021). Among different solutions is the creation of artificial lakes (Fig. 1, Soni et al. 2014; Apostu et al. 2020a; Schultze et al.; 2022; Redondo et al. 2021; Dimitrakopoulos

et al. 2019). The slopes of the old open pit mine and/or the deposits of material, such as dumps, heaps, or backfill, form the lake's borders (Commander et al. 1994). We will use the term dumps in this document covering heaps, slag-heaps and dumps. Pit lakes provide socio-economic opportunities and benefits for the respective mining regions (Lazar et al. 2019).

Several thousand pit lakes have been created on former mining sites around the world. In Australia, at least 1800 pit lakes have been reported (Doupé and Lymbery 2005). In South Africa, about 100 pit lakes have been created in former open-pit coal mines (Johnstone 2018). In the Czech Republic, more than 50 pit lakes were created in abandoned coal mines (McCullough et al. 2020). As the negative consequences of climate change become more obvious, the creation of these lakes becomes more attractive, since they offer the opportunity to enhance the recreational or ecological benefits by re-landscaping and revegetating the shoreline, creating aquatic life, and maintaining water quality. It should be noted that the pit lakes do not always prove 100% beneficial (Hähnel 2016). Some lakes have been closed to the public due to the observed phenomena of flooding, accidental falls, instability, and pollution.

To ensure the safe use of pit lakes, it is necessary to assess the risks in these areas and to develop and apply the appropriate control measures. Moreover, the damage may extend

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Fig. 1 Example of transforming of an open pit mine into a touristic lake and leisure activities (e.g., Albi lake, France, credit Charbonnages de France)

beyond the pit lake. Environmental and public safety are, therefore, likely to be endangered over a wide area adjacent to and downstream of the created lake. It is essential to identify the occurrence and the intensity of these hazardous phenomena in the context of pit lake development (McCullough and Lund 2006; Golder 2016). Within the context of risk management (Chin and Chao 2009), these abandoned mining sites can serve as a catalyst for two distinct outcomes. First, they have the potential to facilitate the sustainable development of the territories within the mining region, while also enabling the creation of water reservoirs, commonly referred to as lakes. Second, they possess the capacity to modify the intensity of existing hazards or potentially give rise to new ones.

The current state of research indicates a notable absence of a comprehensive approach in studying risks related to pit lakes. Thus, the primary aim of this paper is to develop a global risk assessment methodology that encompasses both mining and natural hazards, enabling the evaluation of associated risks specific to pit lakes. Furthermore, this study intends to provide key recommendations for effectively managing these hazards based on their corresponding risk levels. The proposed methodology framework builds upon established and internationally recognized risk management standards, allowing for the evaluation of long-term stability in pit lakes. To illustrate its applicability, the developed methodology is then implemented in the assessment of a pit lake resulting from previous coal mining activities in the Czech Republic.

Risk analysis methodology of pit lakes

The creation of man-made lakes can consequently be associated with hazardous phenomena that could harm the environment and potential users. The specific aim of risk assessment in the case of pit lakes is to reduce the consequences

of new and residual hazards (residual hazards corresponds to hazards after mining activities also known as post-mining hazards) while trying to benefit from the development of the site in complete safety, especially in the long term (Tubis 2020). Therefore, the risk analysis methodology concerns two issues: ensuring safety within and around these lakes (stability) and avoiding pollution of the surrounding environment. In this paper, we suggested a risk assessment methodology for pit lakes and reservoirs considering the mining and the natural hazards. The methodology employed in this study adheres to the principle outlined in Fig. 2 and follows the framework established by ISO 31000 (2009).

The risk analysis methodology for assessing pit lakes consists of three distinct phases (Fig. 2): the informative phase (Step 1), the assessment phase (Step 2), and the risk management phase (Step 3). Evaluating the mining hazard and associated risks throughout the entire lifecycle of open-pit mining operations, from initial stages to abandonment, relies on available data and feedback obtained from comparable phenomena observed at the study site or similar sites, such as slope instability, erosion, pollution, and so on. In the subsequent sections, a detailed description of the relevant data, hazard assessment, residual hazard assessment, and monitoring and mitigation measures is provided.

Data collection requirement for open-pit mine lake

The first phase of the methodology of the hazard identification: mining and natural hazards, the collection, and the analysis of the data. The data required to assess the hazards and risks are mainly collected from archive documents (mining archive, regional archives, etc.), site redevelopment documents and new field investigations and laboratory tests. These data include:

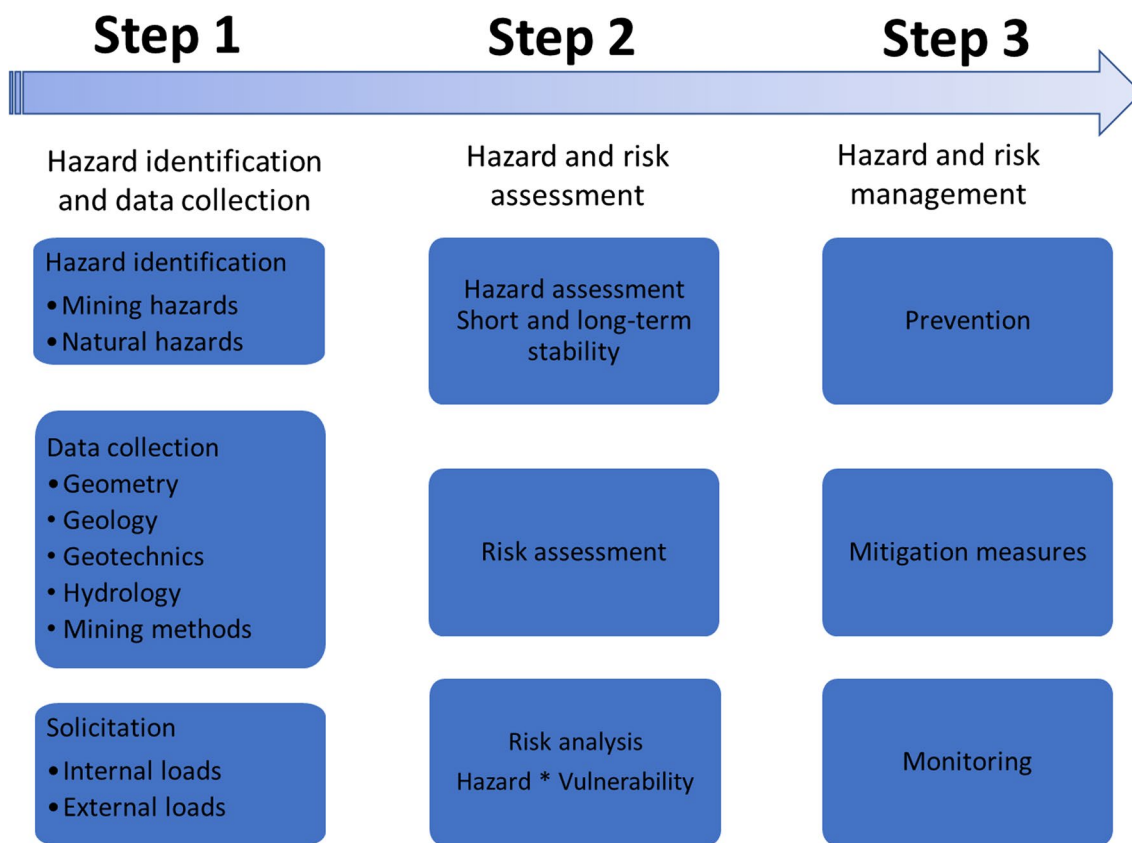


Fig. 2 Flowchart of the risk analysis of open-pit mine lakes

Geometric, geographic and exploitation data:

- The date(s) of impoundment of the lake, the conditions of water rise and stabilisation, the associated disturbance of the lake water inflow and outflow,
- The surface and the volume of the lake, the shape and depth of the pit, the height of the slopes (the exposed and submerged),
- The orientation of the site with respect to the directions of natural or induced fracturing,
- The morphology of slopes and banks,
- The method(s) of open pit excavation and the operating plan,
- The placement (deposition) of waste material associated with the excavation or related to it.

Geological formation, the nature of the rocks, the tectonics, etc., the hydrogeological data:

- The groundwater levels and their potential seasonal variation,
- The water supply sources and water quality,
- The annual precipitation and exceptional rainfall events,
- The site temperature variations and potential evaporation,

- The overburden permeability, in relation to geology and mining operation-induced fracturing,
- The changes in pore pressure or fracture pressure,
- The hydrological disturbances, particularly the acceleration of internal erosion phenomena,
- The flow of water from the surface, particularly during heavy rainfall,
- The natural drainage system and the system specifically designed and implemented for the site.

Geotechnical data:

- The nature and thickness of the rocks and soils,
- The degree of homogeneity or heterogeneity of the terrain, particularly for dumps,
- The fracture and discontinuities and their physical, mechanical, and hydraulic characteristics,
- The mechanical characteristics and the resistance of each soil and rock layers,
- The long-term behaviour of the ground, in particular the effect of water on the mechanical behaviour,
- The nature of the backfill, its thickness and geo-mechanical characteristics must also be collected.

Monitoring system and data measurements:

- The type of phenomena monitored: movement and deformation: inclinometers, photogrammetry, laser scanning, interferometry, water levels and pressure: piezometers, pressure cells, etc.
- The description of site inspection and monitoring methods and systems: density and frequency of measurements (periodic or continuous), data analysis and processing methods, quality and nature of monitoring reports, incident and accident alert and crisis management procedures.

Data related to lake site activities and accessibility:

- The nature of the redevelopment and intended activities: Permanent/occasional activity/Leisure/agricultural/industrial activities,
- The presence in the vicinity of industrial (factories) and agricultural activities, roads, railways, pipelines, dwellings or establishments receiving the public,
- The accessibility of the site by the public or by the services responsible for monitoring and maintaining the site.

Assessment of the mining hazards

The assessment of the mining hazard level is based on a qualitative assessment of factors related to the triggering of the dangerous phenomena, such as subsidence, settlement, landslides or flooding (Castelo Branco et al. 2019; Canbulat et al. 2013; Cirella et al. 2014; Ineris 2018; European Commission 2020, 2022). Although qualitative methods are the most widely used, the use of quantitative, numerical and probabilistic methods is sometimes also recommended, in special cases.

Ground movements hazard

Ground movements, such as settlement, landslide, subsidence, etc., are considered major mining hazards (Bell et al. 2000; Al Heib et al. 2005). Table 1 represents the “ground movements” hazards for a pit mine lake created in a mining site. Six ground movements are identified and described. Their occurrence depends on the configurations of slopes of

the lake: pit and dumps. The "ground movements" hazards can interact with natural hazards (earthquake, change in water conditions, etc.) and could produce cascading effects, for example: the failure of a mine dump leads to the ground sliding into the lake, the increase in the water level of the lake generates flooding of the basin near the lake. The hazard interaction should be assessed and considered for hazard and risk management.

Settlement: The "settlement" of dumps depends on the nature of the dump (Wayne et al. 2008; Hawley and Cuning 2017). It is characterised by its magnitude, several meters, in cases where the following factors have been identified: a clay soil and a significant height of the embankment, and/or a recently constructed embankment or dump and negligible (few centimetres) for very old, low and/or constructed dump. The combination of two phenomena: the settlement of dumps, due to consolidation, and the increase of the lake water level, heavy precipitation, resulting in an overflow of water (overflow) and risk of downstream flooding of the lakes. Additionally, settlement and differential settlement of dumps leads to the formation of cracks. Both phenomena have consequences for waterproofing, drainage, and overflow formation.

Surficial and deep landslide: A surficial landslide hazard corresponds to movements located between 1 and 5 m deep (Behera et al. 2016; Saurer et al. 2013; Sakellari et al. 2021). This phenomenon affects the steepest parts (generally a slope of more than 30°) or the least consolidated and most altered parts. The consequences of a surface slide are generally very limited, and associated with soil erosion caused by runoff on the slope of the dump. The predisposition of a site to developing a surficial landslide also depends on the history of the site, the dump construction method, the contact with water, the heterogeneity in the materials constituting the dump backfill. The presence of fine materials increases the level of this hazard. Certain weather-related conditions are also conducive to surface landslides (Corominas et al. 2014). The depth of the deep landslide (> 10 m) is relatively high compared to the height of the dump, very large volumes can slide, and this can even reach the support layer of the deposit. This concerns both the dump, the open-pit mine pit and the pit lake. This deep landslide phenomenon affects the steepest parts of the dump or the embankment, particularly when clay layers and/or less drained layers are present,

Table 1 Ground movements hazard associated with open pit mining and the mining dump (Ineris 2018)

Slope configuration	Ground movements hazard					
	Settlement	Surficial landslide	Deep landslide	Boulder fall	Mudslide	Creep
Pit–slopes			x	x		
Dumps—Embankments	x	x	x		x	x

The (x): corresponds to the configuration of the pit mine lake where the phenomenon can occur

or when a layer of coal or discontinuous and altered rocky material such as shale, whose dip is unfavourable, is mobilised by the impounding of the lake. The consequences of a deep landslide are severe. Such a landslide can damage land and houses (in the case of an urbanized area) downstream of the landslide zone. If the moving soil reaches the lake, flooding is also to be feared, where waves can also be formed. The flooding can spread downstream and affect works in influence, as well as houses and infrastructure.

Mudslide: A mudslide or mudflow landslide is a flow that is heavily laden with fine sediments resulting from soil erosion (Apostu et al. 2020b), it can concern the dumps. It is a large-scale land movement and associated with heavy precipitation. When large volumes are mobilised, the consequences are destructive, including damage to infrastructure and even human victims downstream. The disaster case study, very well-known, is the Aberfan mudslide of coal dump in UK, causing more than 144 fatalities (McLean 2009). The intensity of this hazard is highly dependent on rainfall. The intensity of the mudflow depends on the volume of soil likely to move or the flow height; evidence of former movements, still visible on the ground or described in archive documents, in a nearby sector presenting characteristics comparable to the site studied are predisposing factors. The volume mobilised depends, in turn, on the height of the dump or embankment, and the thickness of the layer that can lose its structure and start to move.

Rocky slope movements—boulder falls: This hazard mainly concerns the stopes of former open-pit mines used for creating the pit lake. The main predisposing factor is the existence of several families of discontinuities (Pankow et al. 2014). Climatic factors, particularly heavy precipitation can weaken the resistance of these discontinuities and are, therefore, part of the triggering factors of this hazard. Vegetation that has grown around lakes, either naturally or introduced for site redevelopment purposes, can be an aggravating factor for this type of hazard. Seismicity, traffic, or overloading are sources of boulder destabilisation when they are in limited equilibrium state. Poor drainage and variations in the lake level are also factors in triggering boulder falls. The site can also be degraded by human actions, such as modifications to the initial slopes. The consequences can be classified from limited to severe depending on the volume mobilised on the one hand and the conditions of use of the sites on the other. Falling boulders, even in small volumes, constitute a danger in areas of the lake accessible to the public. The intensity classes go from "limited" to "very high" depending on the volume of boulders involved.

Creep: Creep movement of the slope is a ground movement, associated with the presence of clayey soils. The creep movement can be continuous or intermittent, starting and stopping in cycles. It is a physical phenomenon causing irreversible deformations under constant stresses reaching

the plastic domain. It is a slow movement of a mass of soil (with a fine clay or silty matrix) not limited to a clearly defined fracture surface, occurring on slight or steep slopes. It can develop over sometimes significant thicknesses (several tens of meters) and even for relatively slight slopes. The presence of clay must be taken into account when assessing the "ground movements" hazard of surficial or deep landslide type. Since clay is very sensitive to water, the speed of deformation (creep) can, therefore, increase according to the water content.

Erosion hazard and overflow

The erosion hazard mainly concerns embankments and dumps with a significant proportion of fine materials. Water flowing through the porous soil can cause the detachment and transport of certain soil particles (Losfeld et al. 2015; Poulain 2011). The consequences of the erosion can be characterized by the loose land on lake slopes which is exposed to cyclical variation of lake water levels, erosion, and local, even global, instability under certain hydraulic conditions. Repeated wave action can also increase erosion and can cause lake slopes to retreat. The erosion hazard is characterised from the combined analysis of the susceptibility of the dump and embankment soils to erosion (intrinsic soil criteria) and the rainfall factor derived from the medium rainfall and intensity (natural hazard). In addition, the slope of the land and its height, the initial vegetation cover, or the vegetation cover introduced as part of the redevelopment of the site should be considered. The potential susceptibility of a lake site is the result of the combination of soil parameters, slope and erodibility, vegetation, etc. Four intensity classes have been defined from "limited to very high". The overflow can cause the failure of the dumps. The passage of supernatant or effluent over the crest of the dumps can have several origins. It can be linked to a combination of operational and meteorological phenomena, which can be considered, for example, as follows: the water level in the tailings pond is already high due to overexploitation or insufficient drainage; adverse weather conditions, heavy rainfall raises the level in the pond which collects rainwater from part of the site; wind action can play a role if it blows in the direction of the largest side of the pond and generates waves that break on the face, submerge it, degrade it and then create a flow by dragging the crest and eroding the downstream face. Depending on the importance of each of these phenomena and their conjunction, the outcome can be a simple overflow or the beginning of the ruin of the structure.

Fire-self-heating

The fire hazard can affect wooded lake slopes or mining dumps with a significant coal or lignite ratio, due to the

internal combustion of the coal (Singha and Singh 2005). The consequences of this hazard can have various impacts on both the site and the environment. These include burns, asphyxiation, and intoxication of people in the vicinity of the fire and combustion area. In addition, forest fires can be triggered near the lake, especially during drought periods. The risk is significant because the lake area experiences high occupancy. There is also a potential for the dumps to collapse or subside, resulting in overflow and flooding of the downstream land. Furthermore, water contamination can occur due to the release of heavy metals from the combustion, which leads to the release of mineral salts. The heating and combustion hazard are primarily assessed based on the volume and composition of the dump deposit that is prone to burning. The predisposition of a repository to overheating depends on factors such as the materials present in the repository, the presence of thermal observations or measurements (e.g., thermography) indicating a heating mechanism affecting the structure, and the occurrence of similar phenomena in other repositories on the site or in similar configurations.

Water pollution hazard

The water pollution hazard presents a risk for the environment and the population (Younger 2013). The risk assessment related to filling material and water should be based on the identification of local hydrogeological, geological, and engineering, hydrological, climatic, geomorphological conditions, etc. In the context of the pit lakes, it should identify the relations with hydrotechnical structures, groundwater and surface waters, other pollution hotspots, etc. (Schultz et al. 2022). The following pollution should be identified: the emission of contaminants to groundwater from the waste deposited in the lake and surface infrastructures. Water pollution can have significant consequences, including financial, legal, and environmental impacts, as well as

the degradation of groundwater and surface water quality. Furthermore, it can impose limitations on the economic use of water. There is a risk of depleting groundwater resources in the main groundwater reservoir, which may necessitate a reassessment of these resources and, consequently, a modification (reduction) of the reservoir boundaries.

Probability of occurrence of mining hazards

The main mining hazards associated with open pit mines, and consequently with the future pit-lakes, are presented in Table 2. The first step of the hazard assessment is the determination of the probability of occurrence of the hazard. We distinguish between two phases: the construction or flooding (impoundment) of the lake and the post-construction phase, which may include reclamation or reuse of the lake. Three levels of probability of occurrence of the mining hazards are recommended for characterising the mining hazard associated with lakes and reservoirs: low, moderate, or high. According to the feedback and experts, the probability of each hazard existing in this pit lake context is indicated for the short- and long-term. The significance of the hazard about the creation of the lake and its operation is assessed according to the nature of the hazard and its evolution after impoundment. Some hazards retain the same significance before and after impoundment (e.g., landslides), while others become more significant such as creep and heating, due to the increase in the vulnerability of the elements at risk.

Assessment of natural hazards

The closed mines and the created pit lakes can be exposed to the natural hazards that evolve in the area and the lake site studied (Cirella et al. 2014; Rogier et al. 2022). Kappes et al. (2012) presents the list of the natural hazard and their interaction. Thus, several natural need to be analysed

Table 2 Probability of occurrence of mining hazards (11) associated with lake creation; during the impoundment phase (short-term ST) and after (long-term LT)

Hazard		During construction (ST)	Following impoundment (LT)
Ground movements	Settlement	Low	Low
	Surficial landslide	Moderate	Moderate
	Deep landslide	Moderate	Moderate
	Boulder fall, rockslides	Moderate	Moderate
	Mudslide	Low	Moderate
	Creep	Low	Moderate
Hydraulics	Overflow	Low	Moderate
	Flooding	Negligible	Moderate
	Erosion	Negligible	Moderate
Fire	Self-heating-Combustion	Negligible	Moderate
Pollution	Water pollution	Negligible	Low to moderate

to determine their interaction with site-specific hazards, particularly the pit lake. The identification of the natural hazards constitutes an essential step of the analysis. For example, many landslides are triggered by other hazards such as natural seismicity or heavy rainfall, etc. Natural hazards (earthquakes, floods, soil instabilities, and epidemic crises) which can constitute the primary source of risks (Spanidis et al. 2021). Table 3 represents these main natural hazards (20) that may interact with respect to a post-exploitation and potential pit lake reclamation situation. Three levels of interaction are considered based on the feedback and expert opinions: low, moderate, and high are suggested.

Assessment of the risk

The risk assessment is the second step of the developed methodology for the open pit-lake (Figs. 2 and 4). The risk assessment, the impact of the hazards of the elements at risks should be carried out using different analysis tools such as risk matrix, event tree, etc. The event tree method and the fault tree method are qualitative graphical constructions to describe the main event and the occurrence of upstream and downstream events (e.g., ground movements) in a logical way. Figure 3 shows, as an example of risk assessment, the application of the method on a landslide hazard according to the intensity of the hazard (low, moderate and high) based on the parameters (slope angle, soil nature and strength, water impact, etc.).

The evaluation of the level of risk at the lake site (Fig. 2) should be assessed. It is a function of the hazard level and the vulnerability of the entities (people and property) which are or can be found in the short- (creation of the lake and impoundment) and long-term (integration of the lake into its man-made environment, reuse of the water body). Based on the feedback of experts, 3 risk levels are suggested (Fig. 3 and Table 4): no risk or low risk, moderate risk and high-level risk. This level may change in function to the evolution of the lake site. In particular, the development of leisure activities (walking, fishing, bike ride, bathing, etc.) around lakes increases the number of visitors and attracts new people. This "tourist-activities" development is often accompanied by the creation of new infrastructures and installations, which can increase existing risks or/and present new risks.

Hazard and risk management

The last phase of the risk assessment methodology is the management of the risk related to the creation of a new open-pit lake or an existing open-pit lake, based on the identification of the elements at risk and their vulnerability and finally on the risk level. Figure 4 shows a long-term risk management pathway integrating the mitigation and reduction part as well as the hazard monitoring of

Table 3 Summary of natural hazards (20) and their potential interaction in the presence of a mine lake (post-mining or reclamation situation)

Hazard	Description	Interaction	
Climate hazards	Floods	Lowland flooding as opposed to torrential flooding	High
		Flooding by runoff and mudslides	High
		Flooding by rising groundwater	High
	Drought	Shrink-swell	High
		Atmospheric hazards	Cyclones
	Hurricanes		Moderate
	Storms		Moderate
	Lightning		Low
	Hail		Low
	Snow		Low
	Freezing rain		Low
	Forest fires		Moderate
	Land-related hazards	Avalanches	Low
Ground movements		Underground cavities (subsidence, collapse)	Low
		Rockslides, (rock falls, boulder falls)	High
		Slope movements (loose and rocky)	High
		Progression of a coastal dune	Low
		Differential settlement	Moderate
Earthquakes		High	
Volcanic eruptions		Low	

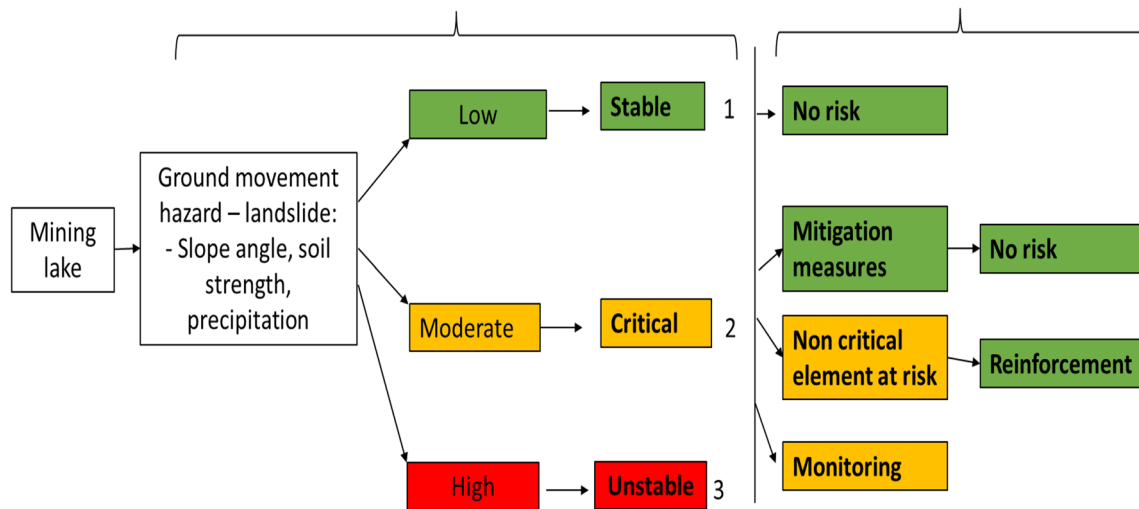


Fig. 3 Event tree developed for a slope stability hazard (open-pit lake) and potential risk and mitigation and intervention measurements, modified from (Chin and Chao 2009)

Table 4 Evolution of the risk level according to the phases of exploitation, impoundment and redevelopment of the lake (LT)

Vulnerabilities	Risk level		
	During operation	Impoundment/creation of lake	LT lake development
People	Low	Low to moderate	Moderate to high
Infrastructures/goods	Low	Low	Low to moderate

the mining site. Mitigation measures, passive and active measures, can be recommended.

Prevention of the hazard and risk

The hazard evaluation led to the risk evaluation based on the elements at risk, mitigation solutions and monitoring. Mitigation measures and monitoring should be addressed for the critical situation to minimise the impact of hazards and maximize the prevention of any potential risk related to post-mining hazards and natural hazards. A prevention of risk plan should be realised covering the pit lake site and the large zone can be impacted by the natural and mining hazards related to the pit lake. They should constitute the essential instrument of the authorities (local, regional, and national) in terms of risk prevention. The objective of this procedure is to control development in pit lake zones exposed to these risks.

Mitigation measures

At this stage of the risk assessment methodology, mitigation measures should be designed to reduce the impact of the hazards. Active measures reduce the intensity or remove the natural and mining hazards. Securing the threatened areas involves work to prevent landslides, drainage, and protective measures against boulder falls and rockslides. Passive measures aim to mitigate the extent of potential damage without influencing the course of events. First and foremost, the extent of potential damage must be reduced. The aim is to ensure that the risks are adequately considered, particularly in relation to the use of the lake. Thus, the level of mitigation measures depends on the site redevelopment (Fig. 4). The mitigation actions are recommended for the areas are only slightly subject to the hazard, where the risk is low or negligible, or to reduce or control the risk in a particular area through specific works such as: reduction of slope angle, land consolidation and reinforcement, water management systems, measures to limit access, setting up monitoring systems, etc.

One important point of the risk assessment methodology is the identification of the residual risk, defined as the risk can be occurred (Adams 2015; Carter 2014). Despite the mitigation measures taken to ensure the lake and the surrounding area after the lake development, a residual risk exists. The acceptable mining risk during the exploitation phase is rather high, especially for material issues. Thus, subsequently becomes lower, especially for sites accessible to the public. Whitman (1984) shows that the failure probability of an open-pit mine is very high but with relatively limited consequences compared to the

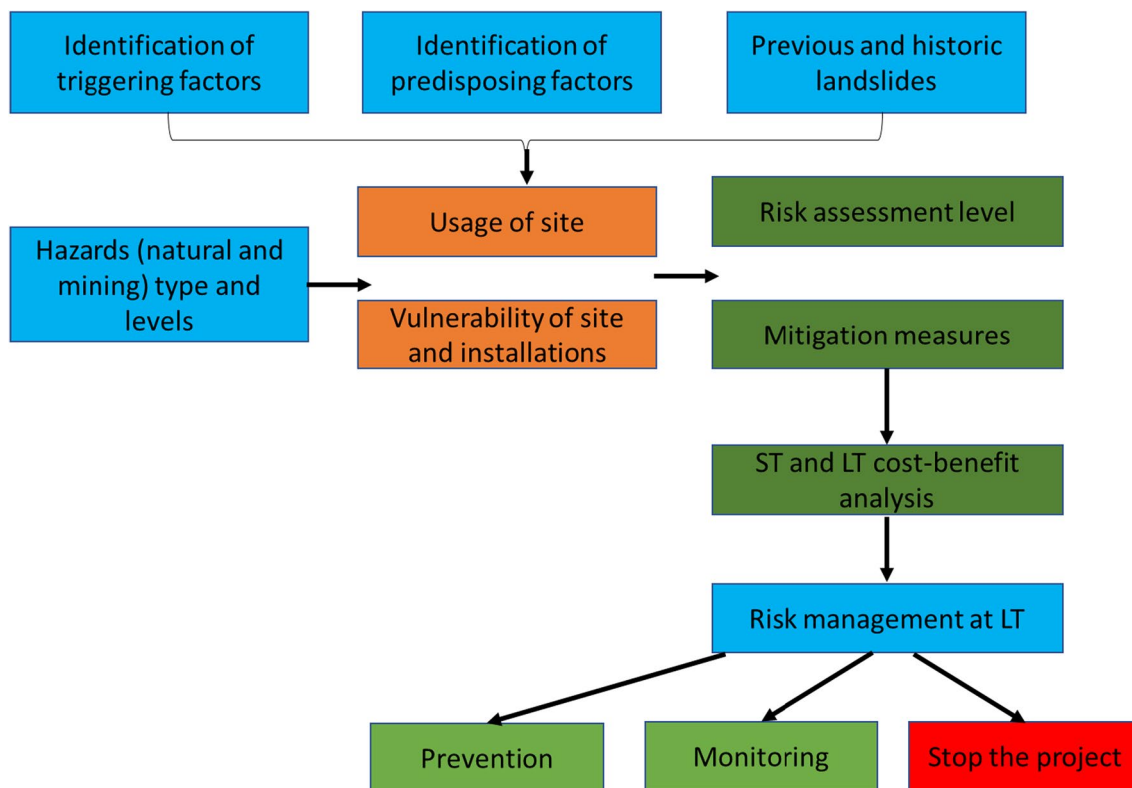


Fig. 4 Risk management strategy of a mine lake

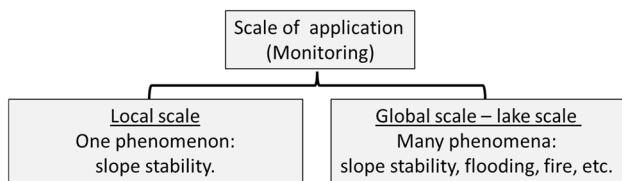


Fig. 5 Application of monitoring according to location and scale of hazard

failure of other types of structures (notably dams). The development of a mine site into a lake or reservoir results in a change in the category and, consequently, in the losses associated with the failure of the structure.

Hazard monitoring

The monitoring of the lake site is part of the risk management (Fig. 4). The concept of a monitoring system is essential for a continuous assessment of the risks associated with the creation and operation of a lake on a former mining site. For instance, the monitoring of instabilities on pit lake slopes is often carried out with the help of multi-parameter systems (deformation, water level, natural and induced vibration, etc.) allowing the combined monitoring of all the physical interactions likely to precede and trigger

the feared phenomenon (Klein et al. 2014). The choice of instruments and devices should be based on the hazard intensities and the site predisposition. It also depends on the local scale of application, generally well endowed with numerous instruments, and a larger scale (Fig. 5): lake, site and/or regional (multiple lakes) scale. Monitoring data, if well-monitored and analysed, are very useful and indispensable for risk management. Three levels of monitoring are recommended for a pit lake: low hazard: no monitoring, or, depending on the vulnerabilities present, minimal monitoring with few dedicated instruments and devices; Moderate hazard: localised monitoring in the most vulnerable areas; moderate-to-high hazard: localised monitoring of the most vulnerable areas with a warning system, and vigilance and alert thresholds. The thresholds of the monitoring parameters must be defined pursuant to feedback from experience and a very good knowledge of the hazards on the site of the lake being monitored. The monitoring must, therefore, be based on procedures that are developed and followed by the various actors involved in the management of the lake site.



Fig. 6 Open pit lake management—Most lake—Czech Republic, before and after management (Credit of VUHU)

Hazard assessment of European mine lakes

General assessment

The data and the hazard assessment for 13 lakes created from former coal and lignite mines in Europe (Czech Republic, Poland, Romania, France, Fig. 6) are analysed and discussed. The quality of the data in each of them with respect to the feared events and thus the mining hazards were then assessed. The following data were analysed: geometric and morphological data, geological data, hydrological data, climatic data, historical operational data, flooding data,

chemical quality of the water, geotechnical data, instabilities data. Table 5 summarises the collected data for the 13 lakes. For a qualitative risk assessment, only one case (Most lake) presents a good quality and complete data, 7 cases present a medium quality data, 3 have a weak quality and 2 without any data. The surface of the lakes varies from 8 to 495 ha, and the depth is generally unknown. The main developing activity is leisure with specific management. One notes a clear lack of information to characterise the hazards, especially the associated risk level. The main hazard cited or identified is the ground movements hazard for three lakes, particularly those associated with landslides (slope stability). The analysis of the authors cases of mine lakes shows

Table 5 Summarized information from mine lakes—former coal mines

Country	Lake	Surf (ha)/depth(m)	Data	Hazards		
			Types	Quality	Known	Predicted
Czech Republic (2)	Most	309/75	GEM, GEL, HY, CL, EX, FL, WQ, GET, VUL	Good	GMT	GMT—Slope stability
	Medard	495/50	GEM, GEL, HY, CL, EX, FL, WQ, GET, VUL	Medium	GMT	GMT
Poland (6)	Lubstow	480/80	GEM, GEL, HY, CL, EX, FL	Medium		
	Dzieckowice (Maczki Bor)	730/12	GEM ?	Absent		
	Morzyslaw	15/3.9	GEM ?	Absent		
	Nieslusz	18.5/?	EX	Weak		
	Goslawice	32.5/?	EX, FL	Weak		
	Kazimierz	65/?	EX, FL	Weak		
Romania (1)	Pestana	154.3/?	GE, HY, CL, EX, FL	Medium		GMT
France (4)	Carmaux	8/230	EX	Medium	No hazards	
	Nœux-les-Mines	220/?	EX	Medium		
	Arjuzanx	400/?	EX	Medium		
	Saint Amédée	13/50	EX	Medium		

Data GEM geometrical, GEL Geological, GET Geotechnical, HY Hydrological, CL Climatic, EX Exploitation, FL Flooding, WQ Water quality, VUL Vulnerabilities, GMT Ground movement

Table 6 Identified mining and natural hazards of the Most lake

Mining hazard (11)	Level	Natural hazards (19)	Level
Settlement	Moderate	Lowland flooding	Low
Surficial landslide	Moderate	Runoff flooding	Low
Deep landslide	Moderate	Groundwater flooding	Low
Boulder, rockslides	Low	Drought	Low
Mudslide	Moderate	Cyclone	N/A
Creep	Moderate	Hurricanes	N/A
Overflow	Moderate	Storm	N/A
Flooding	Moderate	Lightning	N/A
Erosion	Moderate	Hail	N/A
Self-heating – combustion	Moderate	Snow/freezing rain	Low
Pollution	Moderate	Forest fire	High
		Avalanche	Low
		Underground cavities	N/A
		Rockslide	Low
		Slope movements	High
		Coastal dune	N/A
		Differential settlement	Low
		Earthquake	N/A
		Volcanic irruption	N/A

N/A non-applicable

that it is essential to reinforce the collection of data and the realization of the risk analysis.

The Most lake case study

Thanks to the quality of the data of the Most lake, qualitative and quantitative risk assessment analysis were carried out. Table 6 presents the mining and the natural hazards identified after the lake’s creation and filling. One noticed that the lake itself and the adjusted region are exposed to 11 mining hazards and 10 natural hazards. A first qualitative assessment was carried out, based on the collected information and the previous. 2 natural hazards present a high level, 10 hazards present moderate levels (mining hazards) and 8 present low hazards (natural hazards). The erosion, fire and pollution have a severe impact on the environment, mitigation measurements are taken to improve the safety and the security. Additionally, potential interaction between mining hazards (flooding, slope stability, self-combustion) and natural hazards (forest fire, flooding and slope stability) exists. That can increase the risk for the environment and the population from moderate to high level.

The age of the dumps are more than 10 years since coal mining was terminated in 1999. The settlement hazard is high, mainly in the zone of dumps with considerable thickness, however for the oldest and consolidate zones the level of hazard can be lower. Regarding the landslide hazard, the maximum slope angle of the flanks (dumps) is equal to 24°,

Table 7 Probability weights of mining and natural hazards of the Most lake

Mining hazard (11)	Probability range	Natural hazards (10)	Probability range
Settlement	W_3	Lowland flooding	W_2
Surficial landslide	W_3	Runoff flooding	W_2
Deep landslide	W_3	Groundwater flooding	W_1
Boulder, rockslides	W_3	Drought	W_1
Mudslide	W_3	Snow	W_3
Creep	W_3	Forest fire	W_1
Overflow	W_2	Avalanche	W_3
Flooding	W_1	Rockslide	W_3
Erosion	W_3	Slope stability	W_3
Fire	W_1	Settlement	W_3
Pollution	W_3		

corresponding to low hazard. In addition, to the qualitative assessment, an advanced risk assessment was carried using a 3D—large scale numerical modelling, considering the geology and the presence of a weak layer (Renaud et al. 2022). The weak layer has very low friction angle. The result of the numerical modelling showed that the safety factor of the slopes is equal to 2.2 without considering the presence of the weak layer and close to 1.5 when weak layer is considered. Furthermore, in situ observations have shown local instabilities during the construction phase.

Considering the hazards classification in Table 6, a quantitative hazard level assessment can be also performed by considering their probability of occurrence (Lacasse 2011). The hazards provided in Table 6 are already divided in mining hazards and natural hazards. The level of each hazard listed on Table 6 is assigned with a numerical value D_i ($i = 1 \dots 11$ for mining hazards and $i = 1 \dots 18$ for natural hazards). 'Low' Hazard corresponds to $D_i = 1$, 'Medium' hazard corresponds to a value of $D_i = 3$ and 'High' hazard to $D_i = 6$ (Gul and Gunei, 2019; Mohammady et al. 2019). Hazards with null level were omitted completely from this analysis (therefore reducing the number or applicable natural hazards to 10). Based on the literature review (Ward et al. 2020), each type of hazard was assigned to one of three probability categories according to their probability of occurrence (Table 7): W_1 for low probability, W_2 for moderate and W_3 for high probability of occurrence. To calculate the risk distribution, $N = 10,000$ simulations by means of Monte-Carlo were performed (Kwak and Ingall 2007). The value of D_i for each hazard i remained the same across all simulations.

Variable D_i was multiplied with a weight $P_i^{(s)}$ (standing for weight P of hazard i in the simulation $s = 1 \dots N$). This weight $P_i^{(s)}$ has a different, random value in each simulation (s) based on the probability category (W_1 ,

W_2 or W_3) of the hazard i . For W_1 category the probability range is $P=0-0.2$, for W_2 , $P=0.2-0.5$ and for W_3 , $P=0.5-1$ (Verma and Chaudhari 2016; Mohammady et al. 2019). According to Castagna et al. (2015) and Duzgun (2019), the probability of occurrence of each hazard in pit lakes is related to the area vulnerability and, in a significant extent for major hazards, also related to their intensity. The combined risk $R^{(s)}$ for the natural or mining hazards for each simulation is estimated based on the following equation:

$$R^{(s)} = \sum_{i=1}^H \frac{P_i^{(s)} D_i}{\sum_{i=1}^H P_i^{(s)}} \tag{1}$$

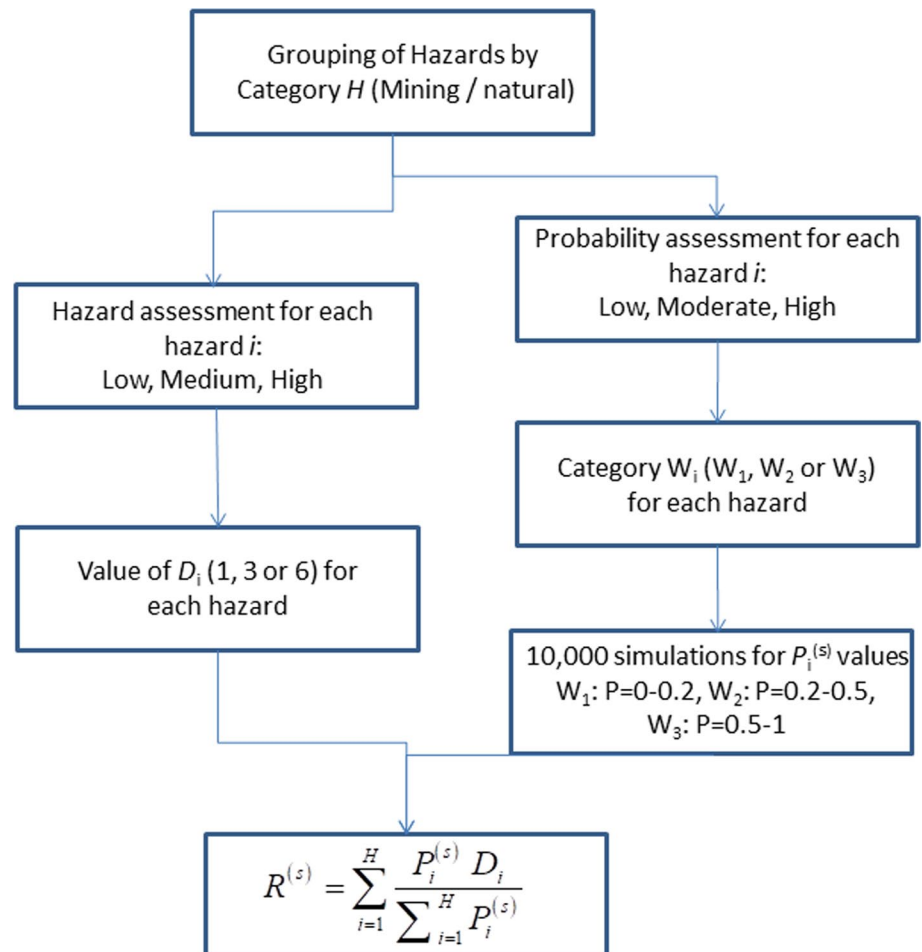
where $H=11$ (H =number of hazards) for mining hazards and $H=10$ for natural hazards. The weights are normalized in order equally process the hazards categories irrespective of their number. Thus, 10,000 different values for R were simulated and presented in the following histograms and cumulative histograms to provide the hazards level R and relative uncertainty bounds. Monte Carlo simulations were performed for the weight $P_i^{(s)}$ only, which is treated as

a random variable. The distribution of $P_i^{(s)}$ is assumed to be uniform within the given probability range for W_1 , W_2 and W_3 . A flowchart describing the process is presented in Fig. 7.

The described probabilistic approach was designed and implemented in Matlab® programming environment. Figure 8 presents the mining hazards risk distribution, and Fig. 9 the natural hazards risk distribution. The mining hazards risk is distributed after the simulations closer to the ‘Medium’ hazard level as well as the natural hazards risk. Although most of the natural hazards belong to the ‘low’ level, the corresponding risk level distribution has a clear trend towards the ‘Medium’ level. The risk distribution quantifies the risk level occurrence considering the hazards impact and probability of occurrence.

Another option for risk level calculation is the consideration of the most significant hazards from each category. According to the literature, landslides and flooding are the most important from each category (Gul and Guneri 2019; Mohammady et al. 2019,). The risk calculation process was retained the same, considering only the relative hazards from each category. Figure 10 presents the risk level distribution

Fig. 7 Mining hazards risk assessment methodology—probabilistic approach



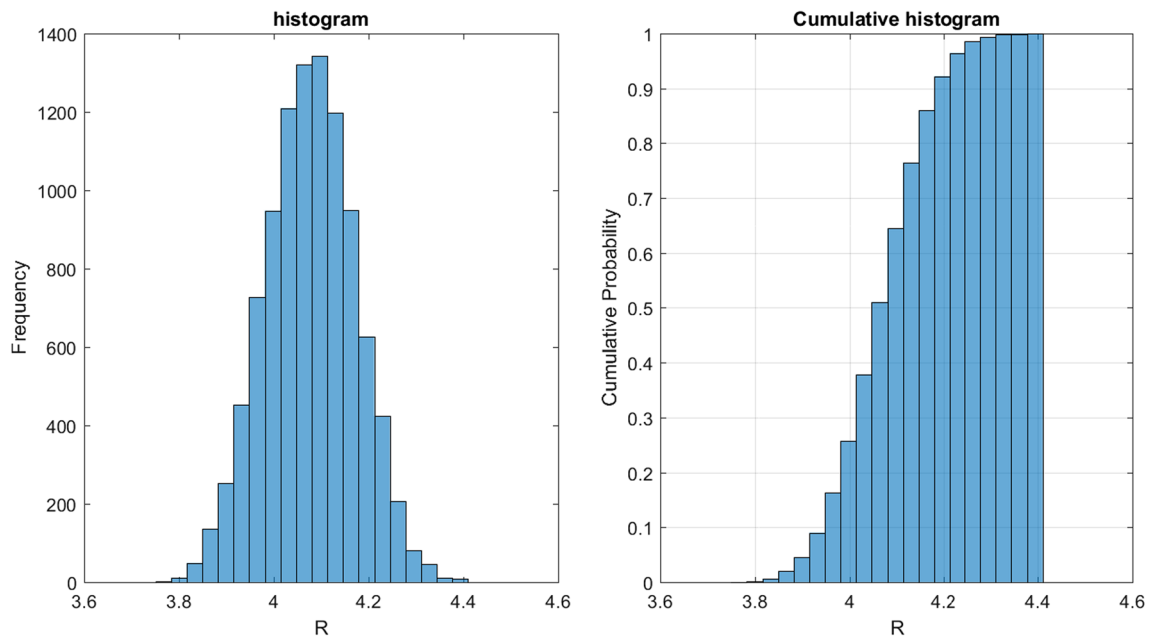


Fig. 8 Mining hazard level distribution (*R*) for 10,000 simulations

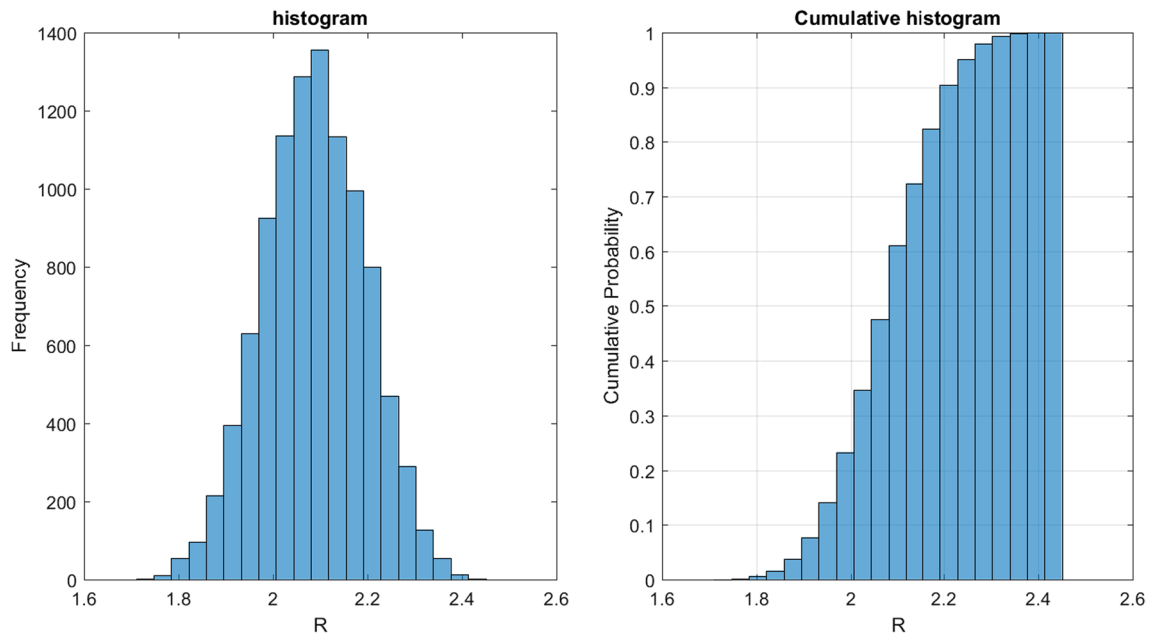


Fig. 9 Natural hazard level distribution *R* for 10,000 simulations

for landslides which can be characterized as medium level (hazard level equal to 3) as distributed after the simulations closer to it, while Fig. 11 presents the flooding risk where its distribution tends to the medium level as well. The latter is an interesting outcome, as all the flooding hazards level were characterized as low. However, the probability of occurrence configures the risk distribution trend.

Overall, the risk quantification performing a simulation analysis presents the risk level distribution of the mining and natural hazards at lake Most. The results considering the hazards impact level and the relative probability of occurrence characterize the overall hazard risk to a ‘Medium’ level.

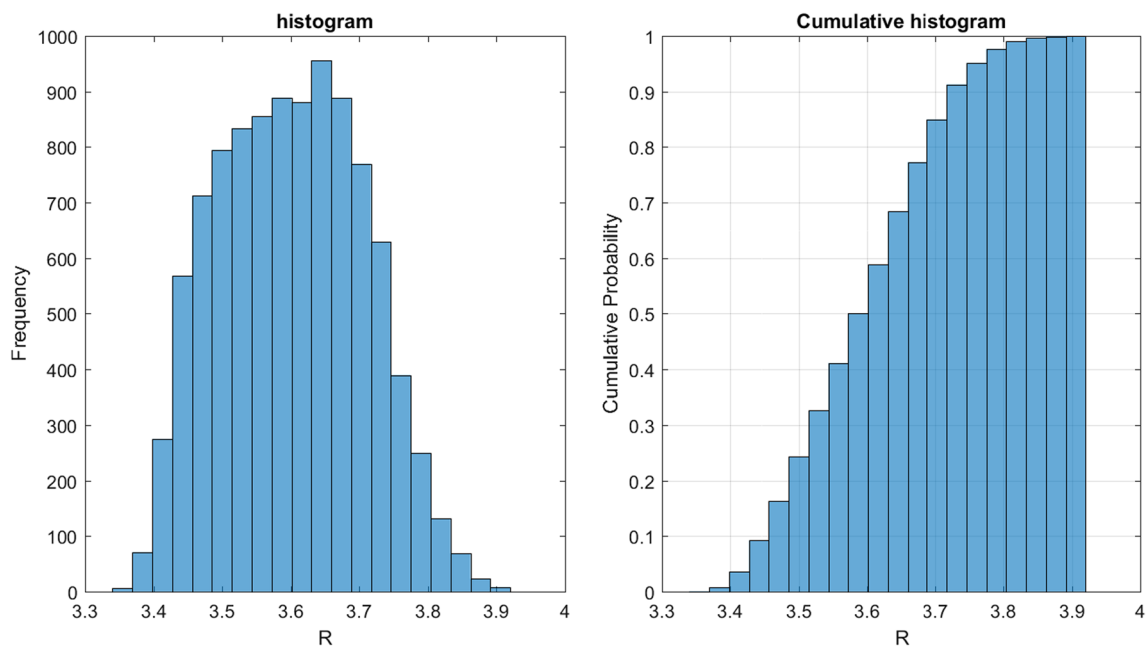


Fig. 10 Landslide hazard level distribution © for 10,000 simulations

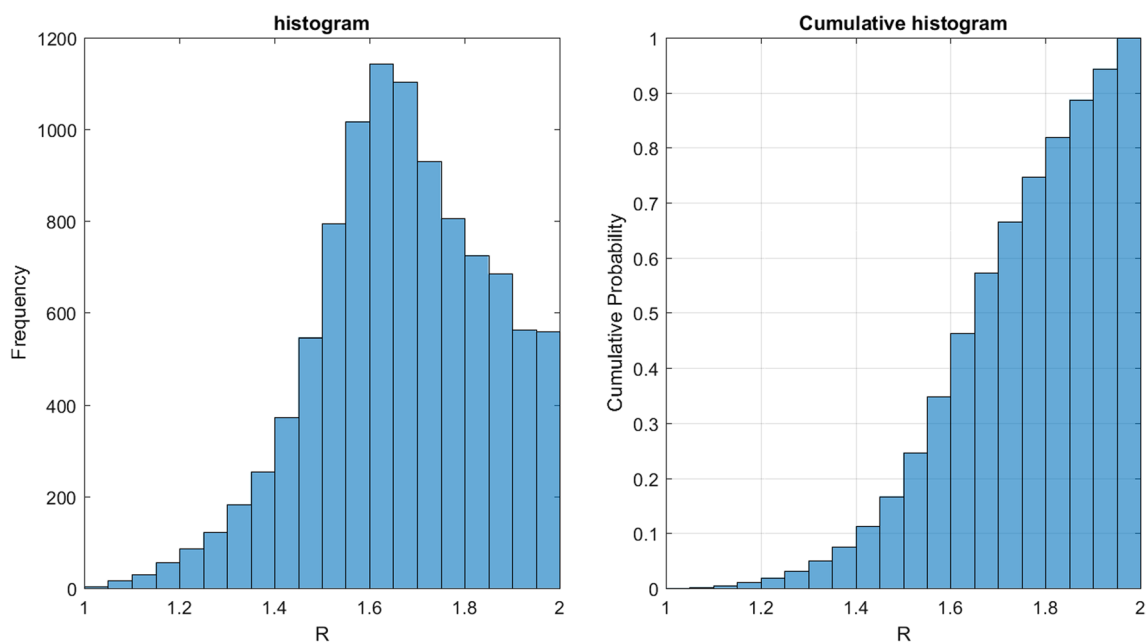


Fig. 11 Flooding hazard level distribution (R) for 10,000 simulations

Based on the geology, the geotechnical data, the in-situ observations, and the calculation results (deterministic and probabilistic), we can consider the Most site presents a low to moderate slope stability hazard. One can observe that advanced and complete risk analysis corresponding to a quantitative method, using different data, can better

assess the hazard and the risk class. The Most site was the subject of different earth and management actions to ensure safety and security for public and leisure employment (Figs. 3 and 6), noticeably, stabilization elements for flanks and roads. The necessary extent of the necessary remediation interventions was elaborated: stabilization

and optimization of the bank line of Lake Most, elaborated. The implementation of the necessary modifications of the peripheral road and anti-abrasive elements of the bank line, resulting from the water management evaluation update, and the operational water surface of the lake was maintained to ensure leisure activities.

Conclusions

This work presented a complete assessment methodology of risks that may affect pit lakes creation in former open pit mines. The main mining hazards in the context of the creation of a post-mining lake, according to our analysis are ground movements (slope stability and landslide), flooding, fire, and risk of pollution.

This paper highlights the different steps that are used to assess the potential mining (11 hazards) and natural hazards (20 hazards) in the context of pit mine lake. The methodology organised through three phases: the informative phase, the assessment phase, and the risk management phase.

To carry out the risk assessment methodology, for each mining hazard, the main data parameters to assess the hazard, the different levels of hazard and the consequences of the hazard were identified and discussed. Two methods are suggested to qualify the level of hazards: quantitative and qualitative. The choice of the suitable method depends mainly on the existing and the quality of the data. In addition, the interaction between natural and mining hazards was discussed. Finally, this paper discussed the management of open lakes as function of the risk level: from designing mitigation measures to stopping the project.

Based on the feedback and analysis, the mining hazards occurrence increases after the construction and the use of the lake. The occurrence of a natural hazard is higher than the mine hazards. This paper highlighted that a particular attention must be paid to the ground movements hazard (slope stability), considering an assessment of the long-term stability of the lake's environment and the impact of any planned reclamation project such as industrial and/or leisure activities.

The application of the methodology on 13 lakes in abandoned coal mine, in Europe, highlighted the need for data investigations. The Most lake which corresponds to an ideal case study, has shown the advantage of the quantitative assessment method. The probabilistic approach provides an alternative way to assess the available information for lake Most. It determines a 'Medium' hazard level based on the weighted assessment of all the hazards that apply on the area. This is similar to the outcome of the numerical modelling where the overall hazard level was determined as low to moderate based on in situ data availability (Renaud et al. 2022).

Overall, creating pit lakes requires an intergraded approach of possible hazards identification, characterization of its potential significance, regular monitoring and update, and a flexible mitigation plan.

Author contributions Conceptualization, M.A. and M.G.; risk methodology, M.A. and all.; probabilistic analysis, E.V.; application on case studies, M.A., V.R. and J.B.; visualization; writing-original draft preparation, M.A. and M.G, Varouchakis; writing-review and editing; V.R. and all. All authors have read and agreed to the published version of the manuscript.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this paper.

Ethics statement This material is the authors' own original work, which has not been previously published elsewhere.

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