

Investigating the biophysical challenges associated with mine closure in different mining methods

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Abstract

Closure issues vary depending on the mining method, creating different biophysical challenges on the surface and underground. In turn, mining methods depend mainly on the geology of the ore deposit, which itself is defined by regional characteristics, such as morphology and local tectonics, etc. The closure is an important factor in developing and planning new mines but is often subordinate to other factors. The mining method is often selected based on pre-feasibility studies and there is limited ability to change the operational characteristics once implemented. If the ability to close the mine, re-use the landscape and contribute to the community and post-mining economy is to become driving factors in the selection of the mining methods and subsequent mine operations, then they should also be carefully considered in early decision-making.

A few new mining methods have been proposed for zero-entry and invisible mining that leave waste in place and reduce ore movement. Since these methods require the use of alternative technologies, such as robotics for automation, leaching, and efficient cutting, they will introduce a different set of biophysical issues that will affect the closure and post-mining land use. The potential benefits may be outweighed by their risks, or they may introduce a new set of opportunities for closure at a lower cost and with minimal biophysical risks.

This study has, therefore, aimed to compare the biophysical closure impacts of conventional and novel mining methods and to identify if the new mining methods, especially in-place mining, support a business case for closure that enables and motivates the industry to adopt these new mining methods. We identify, compare, and contrast biophysical impacts on post-mining land use for in-place mining methods relative to more traditional mining methods using desktop studies, workshops, and interviews with member company representatives. The study also identifies opportunities to use new mining methods that enable alternative closure options. The study develops and uses a comparative matrix that compares the biophysical impacts of novel mining approaches with the more traditional mining methods (e.g., open pit mining, underground stope mining, and cave mining). The study highlights the current problems, identifies transformational opportunities, and determines future activities that could enable mining methods with improved closure outcomes. The biophysical impacts of different methods should be compared quantitatively, although the current reference site approach has flaws. The use of the rock engineering system enabled quantitative analysis of the survey data, though highlighted that many experts are unaware of the biophysical impacts at closure. The findings also show that the new mining methods are expected to modify and reduce the closure issues relative to the conventional mining methods, which often require large open pits, voids underground, and large tailings footprints. Further investigation is needed to further develop the novel mining methods and to evaluate the applicability of the methods for local small operations as the transition point to full-scale adoption.

Keywords: *biophysical impacts, new mining methods, open pit mining, underground stope mining, and cave mining*

1 Introduction

Mining impacts can generally be classified as biophysical, ecological, and socio-economic impacts. Biophysical impacts, however, mainly refer to parameters that represent the biotic and abiotic components of the local environment. This includes the diversity of plant and animal life in the area, together with the physical environment that is made up of components such as relief, soils, water, and the atmosphere (Sango et al. 2006). A wide range of environmental and social impacts emerge both during and after mining operations, including communal contamination of soil and water (e.g., acid mine drainage), and pollution of the local and regional air (Sango et al. 2006). An important factor that must be considered in mine closure is to design a closure plan to ensure continued livelihood for the local community through diversification and community empowerment (Anon 2016a, 2018). Although the mining industry strives for efficient technological advancements and innovation in mining techniques, the actual contribution of these techniques to the prevention of environmental and social impacts must also be carefully investigated (Vela-Almeida et al. 2015).

Closure issues vary depending on the mining method, creating a unique set of biophysical challenges on the surface and underground. On the other hand, mining methods depend on the geology and, to some extent, the geomechanics of the ore deposit and the surrounding rocks (ISRM 2008). Typically, the method is selected based on pre-feasibility studies (Mackenzie & Cusworth 2007; Nicholas 1981, 1993; Saki et al. 2020) and changes are limited once implemented due to the capital invested into the equipment, layout, and mine design, along with the investment cases identified. If the environmental impact of the mining (ISRM 2008; Samimi Namin et al. 2011), the ability to close the mine, re-use the landscape and contribute to the community are to become driving factors in selecting the mining method and mine operations, then they should also be considered earlier in the decision-making to improve the sustainability of the mining method and to reduce the environmental footprint of the mining. Currently, no consideration is given to biophysical challenges with typical criteria for mining method selection (Ataei et al. 2008; Bitarafan & Ataei 2004; Bogdanovic et al. 2012). Including the biophysical legacy issue as a more relevant factor in the feasibility studies is an initial step toward making mining more sustainable in the long-term (Samimi Namin et al. 2011).

Moving and processing rock to extract a small percentage of valuable metal represents over 90% of energy and 80% of the total production costs in mining (Anon 2007; Powell & Bye 2009; Wang et al. 2013). This inefficient consumption of energy can be environmentally disruptive due to the required footprint for processing and storing the waste material (Jeswiet & Szekeres 2016). Large-scale gangue movement and treatment drive operating costs and set higher cut-off grades that require the mining methods to produce in an economy of scale (Hartman & Mutmanský 2002; Hustrulid et al. 2013). To address the large footprint of current methods, novel mining methods have been proposed (Mining3 2017; Mousavi & Sellers 2019; Rossien 2018; USBM 1994). The main consideration required for transformational methods are encapsulated into methods that have reduced operational costs, zero-entry, invisible mining that leaves waste in place, and reduces ore movement and processing. Since these methods require the use of alternative technologies, such as robotics, leaching, and cutting, they may introduce a different set of biophysical issues that may affect closure and post-mining land use. Therefore, there is a need to close the gap and quantify the biophysical impact of different mining methods, especially of any future mining method. Given the mine of the future will likely be very deep and targeted, they must have a minimum footprint, much lower energy requirements, and only bring to the surface the primary products required by an increasingly circular economy (Batterham 2017).

The study aimed to identify the main biophysical issues involved in mine closure, where possible, with real-life examples of good and bad practices from the literature and the mining government and METS partners. The objective of the study has been to understand what knowledge exists in the relationship between mining methods and biophysical impacts that must be addressed during mine closure. The first step of the study involved categorising the mining methods to identify and evaluate their closure challenges. Then, a survey was used as an approach for collecting experts' opinions on relative impact. This enabled the novel mining methods to be compared with conventional methods to identify opportunities to change closure options and highlight closure challenges.

2 ESG and biophysical considerations for mining

The critical commitment of mining and the mineral area towards the advancement of the neighbourhood and public economies overall is certain. Mining operations have been providing key development inputs to communities. Examples of inputs include social services, infrastructure, and employment. The high levels of industrial and overall economic development achieved in Western Europe, North-eastern USA, and the Rand region of South Africa are partly attributable to the mining industry (Anon 1992; Solomon 1999; Viewing 1982). While the indicators of economic growth associated with mining are easy to measure and appreciate, the question remains: to what extent is the mining sector an effective driver of sustainable socio-economic development and environmental management at the local level? This is a cause for concern, particularly during the post-mine-closure era (Karombo 2020). In other words, to what extent does a given mining operation contribute toward the continued sustainable existence and development of the local community, particularly after the eventual closure of the mining operation?

Bearing in mind the new ESG risks and challenges for the mining operations (Stacey & Hadjigeorgiou 2022), mining companies have started thinking about new mining methods that can reduce the environmental footprints of the operations. Such innovative mining methods can also reduce the capital costs and the amount of development, and subsequently shift the cut-off grade toward much smaller values. Implementing these revolutionised mining methods (e.g., in situ and in-mine recovery) can unlock access to a significant amount of resources to which their extraction was not feasible through the conventional mining methods (Batterham & Robinson 2019; Mousavi & Sellers 2019; Rossien 2018). Not only can this significantly affect the environmental problems related to mining but can also improve the life-of-mine and the associated social-economic problems of the communities close to and engaged in the mining activities (Robinson & Kuhar 2018).

A wide scope of ecological and social effects arises both during and after mining activities. Some models incorporate the annihilation of the normal scene, local vegetation, and natural surroundings. This comes full circle into the loss of biodiversity. Others incorporate the degradation of soil and water, contamination of the neighbourhood and local air, the hardship of arable and pasture land, impingement of human wellbeing and security, including outrageous instances of death and the making of phantom towns, and forsaken scenes (Crowson 1998; Sonter et al. 2018; Tilton 1996; Young 1992). The mining business has shown it is pivotal in the social framework at local and global levels. Nevertheless, the hopeful image of the mining business in creating benefits is vulnerable to risks and flawed communication. These risks incorporate political and social precariousness, mineral asset consumption, ecological and wellbeing hazards, and, in particular, changing micro- and macro-economic conditions that can make asset extraction troublesome, expensive, and unviable. Some mines may close, leaving the surrounding local area helpless against antagonistic social and natural effects. Tilton (1996) proposes that the exhaustibility of mineral assets comprises the fundamental guideline of preservation in mining plans. At closure, the environmental management challenge for the mining operator is to re-establish the land to its original land use. Hutchinson et al. (2002) also referred to the Canadian Government guideline for effective mine rehabilitation in which the main objectives are, first, to protect public health and safety; second, to alleviate or eliminate environmental damage; and, third, to allow productive use of the land like its original use or an acceptable alternative. For example, according to Hutchinson (2000) and Hutchinson et al. (2002), assessing the stability of mines is an essential factor for mine closure planning and any potential post-mining land use. The physical stability of mining excavations is important because any instability can damage the surface and potentially impact the post-mining land use. The long-term stability assessment for closure planning should account for the long-term physical and chemical stability of the ground and surface water. It should also include the physical stability of any remaining surface and subsurface structures and excavations (which can potentially affect the surface). The latter includes excavations such as pits shafts or crown pillars.

Defining and identifying the relevant biophysical issues is a key component of connecting with planning and production-focused mining engineers. Sango et al. (2006) considered biophysical criteria associated with mine closure to include landscape/land quality, state of vegetation/fauna, state of the soil, water resource

quality, air quality, state of arable/pasture land, environmental quality of the residential compounds and health and safety, and risks. One of the main concerns is the alteration of the land surface in the form of excavation, dumped rock waste, or a concentration of scrap equipment and concrete pavements. Consequently, vegetation, soils, fauna, and drainage are adversely affected, with no rehabilitation work being observed on the ground. Several studies have also evaluated the local impacts and categorised the biophysical variables as biotic and abiotic components. Different local biophysical variables are considered to quantify the impact of the mining method used. For example, Blanchette & Lund (2017) have only considered the implications on the water in rivers while Firozjaei et al. (2021) recommend considering land-use and land-cover impact from mining using the surface biophysical characteristics, notable changes in the pattern of vegetation cover, and land surface temperature.

When measuring the closure outcomes and impacts, consultants will compare impacted sites to a 'reference site' that is broadly perceived as having desirable conditions, processes, and outcomes with which to compare impacted sites. Generally, reference sites co-occur with disturbed sites, yet are unimpacted and retain the 'naturalness' of the biota (Stoddard et al. 2006). However, this approach can be perceived as flawed by creating impossible or unrealistic targets for miners seeking to close rehabilitated lands. For example, many systems are so heavily modified that co-occurring unimpacted sites do not exist (Chessman & Royal 2004).

The Leading Practice Handbook: Mine Closure from the Australian Government's Department of Industry, Science, Energy and Resources (Anon 2016a) provides a more extensive set of biophysical issues with potential options for quantification and could be a framework for studying each of the new mining approaches in more detail. The handbook appendix indicates that the mining issues to be considered are underground voids and shafts, open-pit pits, underground voids and shafts, tailings storage facilities, waste rock landforms, mine townships, water storage dams, and service infrastructure. It is notable that their categories are not uniquely defined and may have different meanings for different people.

3 Description and categorisation of mining methods

The selection of a suitable mining method for an ore deposit requires the consideration of numerous criteria, such as mining-geological factors and economic factors, and needs to include biophysical factors (Horváth et al. 2016; Saki et al. 2020). With the current situation, the discovery of new deposits (Murphy 2022) is becoming rarer, and extraction is related to technology and methods we have available today, the profitability for ongoing mining methods with defined capital and operational cost is limited. Sustainable closure adds considerable cost and additional considerations to standard mining methods (Anon 2016b; Fourie & Brent 2006; Limpitlaw 2004). There are cases where a transition from surface mining to cave mining occurs due to the increase in depth of orebody (Figure 1a).

Conventional mining methods (Abzalov 2016; Hustrulid et al. 2013) often require large open pits, voids underground, and large surface subsidence and tailings footprints (Figure 1b). New mining methods could disrupt this process with different cost structures that may enable currently unfeasible deposits to be explored. But new mining methods may also bring unknown risks that can be a challenge for mining operations and closure.

There are many different mining methods available (Abzalov 2016), and so in this preliminary study, it was prudent to classify the methods into as few different options as possible. A simple classification for underground options is listed in Table 1. After workshoping options, a simpler approach was taken. All stoping options were grouped together (including cut-and-fill and vertical crater retreat), as were all caving methods. The final set of categories is described briefly below.

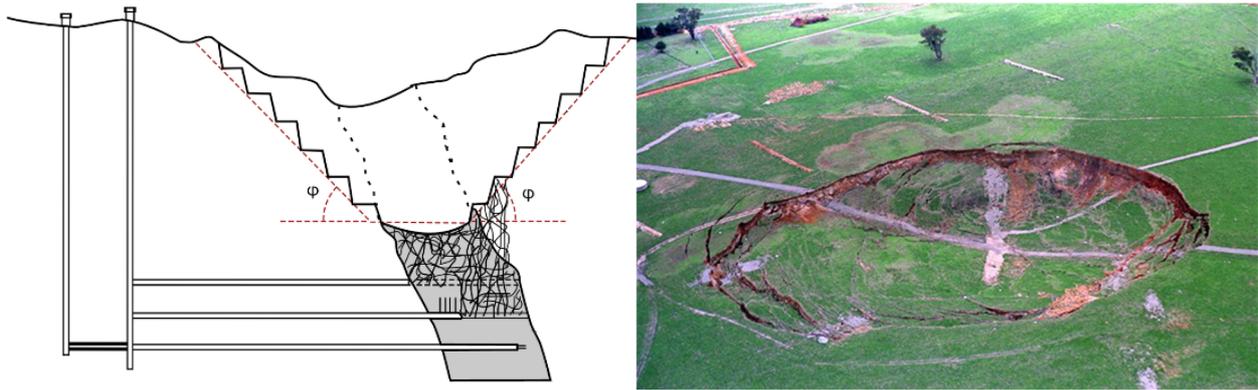


Figure 1 (a) Transition from open pit to cave mining (adapted from <https://upload.wikimedia.org/wikipedia/commons/f/f7/Ug-mining-greek.svg>); (b) Example of surface subsidence in cave mining (adapted from <https://en.wikipedia.org/wiki/File:Elura.png#file>)

Table 1 Classification of underground mining methods (adopted from Lung 2020)

| Class | Description | Mining method |
|-------|---|-------------------------------|
| I | Naturally supported | Room and pillar |
| | | Sublevel stoping |
| | | Open stoping |
| | | Vertical crater retreat (VCR) |
| II | Artificially supported | Cut-and-fill mining |
| | | Shrinkage stoping |
| III | Cave mining | Sublevel caving |
| | | Block caving |
| | | Longwall mining |
| IV | Innovative in-place and solution mining | In situ leaching |
| | | In-mine recovery/leaching |
| | | Inline recovery |

3.1 Surface mining methods

Surface mining is a method of extracting minerals near the surface of the Earth (Abzalov 2016). Waste and ore are extracted by removing the covering layer of rock and soil with high material movement and low selectivity.

3.1.1 Open pit mining

The open pit mining method (see Figure 2) is one of the surface mining methods that have a traditional cone-shaped excavation usually used to exploit near-surface, non-selective, and low-grade zone deposits in horizontal exploitation stages (benches). It often results in high productivity and requires large capital investments, low operating costs, and relatively good safety conditions.



Figure 2 (a) An example of an open pit copper mine (adopted from Cristian Bortes, Wiki Media Common, https://commons.wikimedia.org/wiki/File:Ro%C8%99ia_Poieni_open-pit_copper_mine.jpg); (b) Opencast coal mine (adopted from James Allan, Wiki Media Common, https://upload.wikimedia.org/wikipedia/commons/5/5c/Open_cast_mining_-_geograph.org.uk_-_142590.jpg)

3.1.2 *Opencast mining*

Similar to open pit mining, opencast mining is usually employed to exploit a near-surface mineral. The major difference is that it focuses on tabular deposits, such as coal, and blasting aims to cast overburden away by blasting to allow access to a coal seam. Thus, a strip of open mine moves across the landscape. Opencast mining often results in high productivity and requires large capital investments, low operating costs, and good safety conditions. Both open pit and opencast mining methods generate a large amount of waste.

3.2 *Underground mining methods*

Underground mining methods (Abzalov 2016), on the other hand, require further development to reach the depth deposits when the ratio of ore to waste is low enough to prevent economic extraction by a surface mining method. The ability to dig into the ore allows for a better selectivity of what to extract, in comparison to a surface mining method, without the need to remove as much waste. From a geomechanical perspective, the underground mining methods can be classified based on the type and degree of support required in the mining operations, with an increase in rock movement from the pillar supported to the unsupported pillar and a decrease of energy stress/energy storage in the country rock. There are intermediary methods that sit between these methods (e.g. sublevel stope mining), with room and pillar and caving mining being at the extremes in this range. In some cases, a combination of surface and underground mining is seen, such as the transition from open pit mining to cave mining, due to an increase in depth (see Figure 1).

3.2.1 *Room and pillar mining*

This method (see Figure 3a) involves creating open areas within the orebody and leaving pillars of rocks at consistent intervals throughout the open area to support the rock structure above. After mining out the ore within the area, the pillars may be removed for safe collapse, sometimes with fill added to the resulting cavity. It is not usual for this to occur in very deep mines, as the width of the pillar would be too wide to support the stress.

3.2.2 *Stope mining*

A variety of stope mining methods are available (open stope, sublevel open stope, cut-and-fill stoping, shrinkage stoping) (Abzalov 2016). The operation (see Figure 3b) consists of drilling and blasting material, leaving behind an open space known as a stope. Stoping is used when the country rock is sufficiently strong not to collapse into the stope. Material is then collected from drawpoints at the bottom of the stope. This mining method is relatively safe, as the mine retreats away from the previously mined or unsupported area of the underground mine.

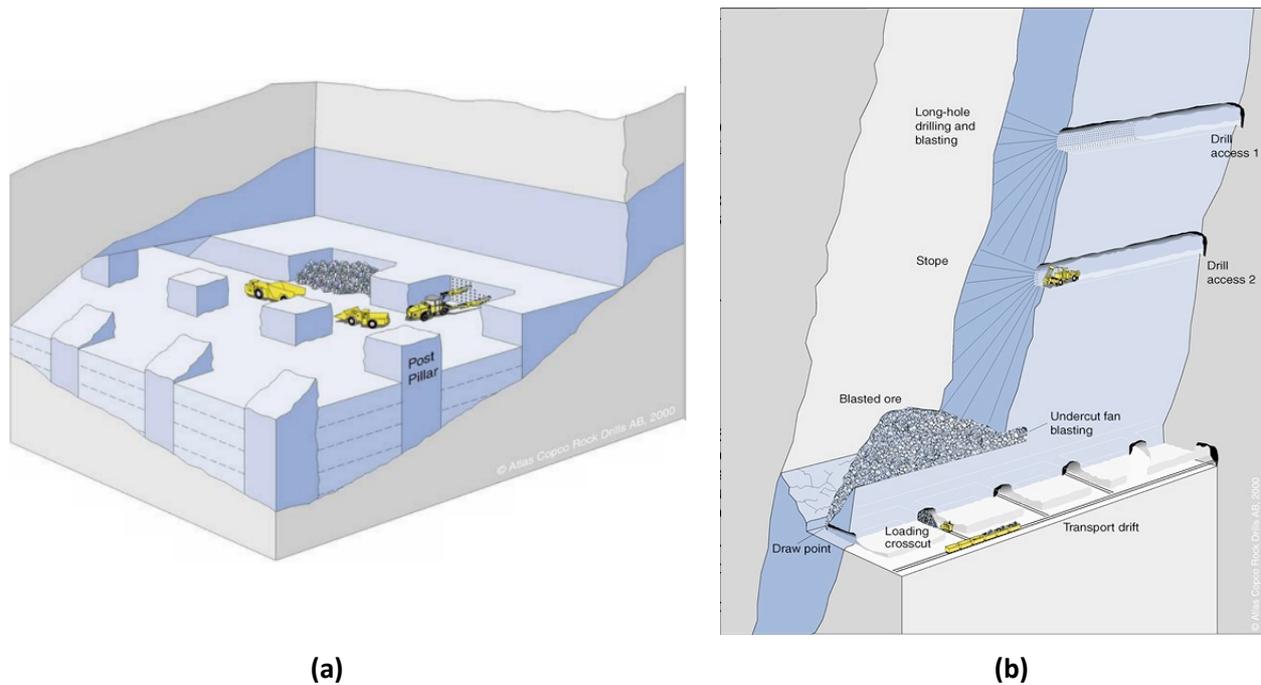


Figure 3 (a) Schematic view of room and pillar mining method; (b) Schematic view of sublevel open stope mining method (Courtesy of ISRM 2008, but originally credited to Atlas-Copco 2000)

3.2.3 Caving mining

This method (see underground mine in Figure 1a) focuses on undermining the ore at locations where its structural integrity will be compromised, forcing it to collapse under its own weight (Chitombo 2010). Once the overlying rock mass is compromised by its own weight (block caving), or by blasting in harder rock (sublevel caving), and has fallen into drawpoints, the ore is excavated by load and haul equipment (Abzalov 2016). This method is highly productive as it usually requires lower running costs than conventional methods of mining, although more preparation and capital costs are necessary, and access can be difficult. The cave mining method can result in significant surface subsidence (see Figure 1b)

3.2.4 Longwall mining

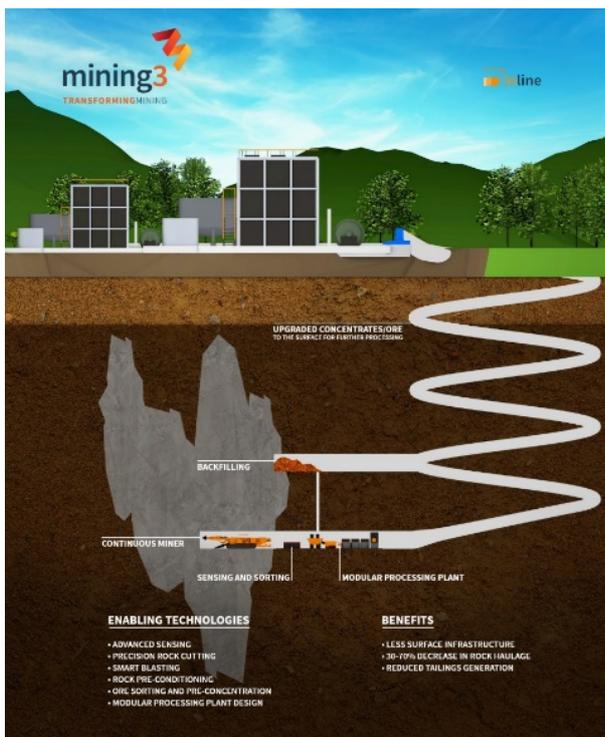
This method involves the mechanical excavating of minerals from tabular deposits. Typically, these are coal mines as well as soft mineral deposits, such as potash. Large rectangular blocks of coal are defined during the development stage of the mine and are then extracted in a single continuous operation (see Figure 4a), usually with equipment that cuts the face of the rock. Shallow longwall mining methods can create large-scale impacts on the surface, such as subsidence (see Figure 4b). Longwall and room and pillar mining are used in deep-level hard-rock mines, typical in South Africa (Malan & Jooste 2019). These mines do not cause the same deep surface subsidence issues but create significant biophysical and social issues due to the volume and aggressive composition of the tailings (Mangwaya et al. 2021).



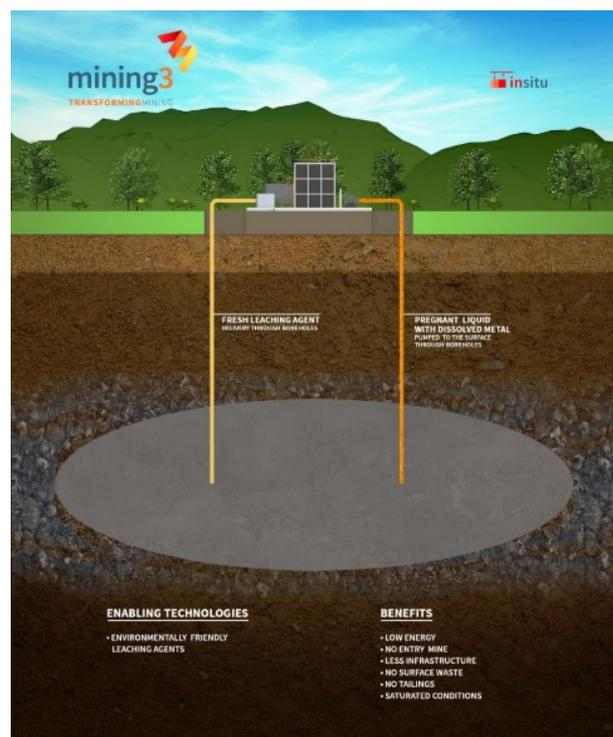
Figure 4 (a) Schematic of ground surface subsidence due to longwall mining; (b) Example of the large-scale biophysical impact of a longwall failing into a slope (Salmi et al. 2017)

3.3 Innovative mining methods

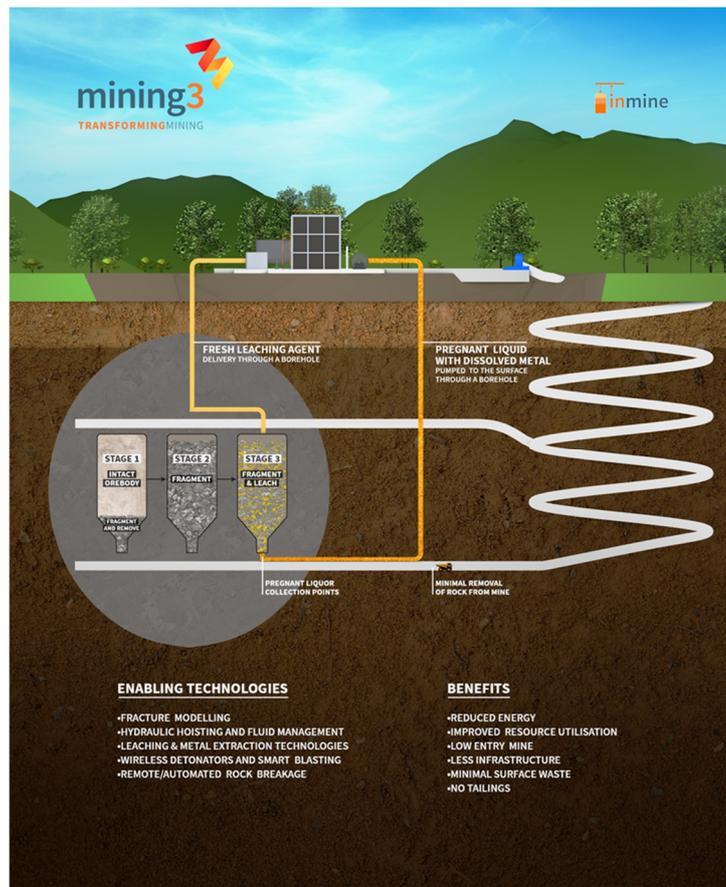
Mining3 is leading an initiative called in-place mining, which is motivated by the concept of minimal rock movement and processing ‘in place’. In-place mining will deliver a small surface footprint, reduced tailings generation, high automation, and a low capital intensity mine. The innovative in-place mining methods include inline mining, in situ mining, and in-mine recovery, which are shown in Figure 5a, Figure 5b, and Figure 5c, respectively.



(a)



(b)



(c)

Figure 5 Schematic views of (a) Inline mining; (b) In situ mining; (c) In-mine recovery (Mining3 2017)

3.3.1 *Inline mining*

Inline technologies are deployed ‘at the face’ to selectively mine, sense/sort, and process ore (see Figure 5a). Concentrated material is transported to the surface processing facility and waste is left underground. Enabling technologies include advanced sensing of the rock mass, precision rock cutting equipment, smart blasting techniques, ore sorting and preconditioning, and a modular pre-concentration plant. The Inline mining concept aims at selective mining and ore upgrading, and then a concentrated material is transported to the processing facility. This mining method incorporates technologies that can be used at or close to the face for selective mining (usually underground). It is expected that the pre-concentrated materials reduce the need for haulage of material to the surface for processing. Some of the technologies include the DynaCut mechanical cutting machine, mobile crushing, sensing, and sorting units, and Gekko pre-concentration technologies.

3.3.2 *In situ mining*

In in situ mining, the ore is processed using leaching fluids circulated through the fractured rock between a grid of drill holes (Abzalov 2016; Kuhar et al. 2015; Robinson & Kuhar 2018; Sereдкиn et al. 2016) (see Figure 5b). One of the main challenges in in situ mining is identifying and evaluating ore deposits suitable for in situ recovery. Developing techniques and technologies for creating direct access pathways to target minerals is a key to the success of the projects. Considering the hydrogeological features of the mine site, the design of fracturing for improving the permeability of the ore, having access to non-toxic lixiviant technologies, and leaching systems are also vital elements. Traditional in situ leaching is a well-known technology, allowing a low-cost method for commodity extraction that does not depend on rock movement since the ore is processed in situ in surface operations. One of the main risks of in situ mining risk is related

to the social and environmental concerns associated with the application of conventional acid and cyanide lixiviant (Batterham & Robinson 2019; Kuhar et al. 2015). However, the application of the newly developed environmentally friendly lixiviant can help to control and mitigate such risks. A key enabler for revisiting this technology is the development of new lixiviants that appear to be non-toxic, non-volatile reagents. Typical new lixiviants include glycine (Breuer et al. 2012; Eksteen et al. 2016; Tanda et al. 2017). Many of these lixiviants can leach base and precious metals without taking gangue minerals into the solution and can also be reusable.

3.3.3 *In-mine recovery*

This method is proposed as an alternative to in situ recovery when the rock is insufficiently permeable to allow the unimpeded flow of leaching fluids. The aim is to fracture ore using blasting/hydraulic or other means and leave the rock in place to be dump leached by chemical or biological methods that extract only the valuable ore under unsaturated conditions (see Figure 5c). Enabling technologies are fracture modelling, hydraulic hoisting, non-toxic lixiviant technology, leaching systems, and remote/automated rock breakage systems. Various designs are possible to create mining methods where conditioned mineral blocks can be leached underground. For example, the CSIRO Remote Ore Extraction System (Anon 2002; Boyce & Minchinton 2017) uses remote automated horizontal drilling and blasting to expand a vertical raisebore as a possibility of creating an underground leach reactor for massive leachable deposits (Rossien 2018). Another possibility is a hybrid method where high-grade ore can be treated more conventionally and low-grade ore is 'dump' leached in underground reactors, increasing the recovery of the deposit while keeping the material movement to a minimum (Mousavi & Sellers 2019). This would allow for revisiting brownfield mine sites to extract residual value in the remaining ore with lower capital costs.

4 Does mining method selection include biophysical considerations?

Managing closure risk is an integral part of mine planning and management, and a risk management system can enable an operation to identify the risks and develop controls associated with sustainable mine closure and achievement of mine completion. An effort to standardise closure evaluation has been started across Australia with the aim to diminish the biophysical impact of mining. Closure and rehabilitation legislation has been put into place in most regulatory environments and linked to guidelines for mining engineers (Blommerde et al. 2015). Mining method selection is the most important decision made in a mining project (Bitarafan & Ataei 2004; Saki et al. 2020) as it drives the final economic value for shareholders. Multi-criteria decision-making (MCDM) methods, such as analytical hierarchy process (AHP) (Saaty 1980, 2008) or ELECTRE (Roy 1990), which are commonly used for mining method selection, make the evaluations using the same evaluation scale and preference functions on a criteria basis (Bogdanovic et al. 2012). However, even the most recent papers, such as the work by Balt & Goosen (2020), indicate that mining consultants often do not consider anything other than orebody characteristics in the mining method selection

In a recent study, Saki et al. (2020) also investigated the applicability of different MCDM approaches for the selection of the best mining method. A list of 50 parameters, including geomechanical, topographic and geometrical, technical, economic, environmental, and social factors, was considered for the selection of the most optimal underground mining method. Experts' opinions were then collected and used to refine this list to the most influential parameters (see Figure 6).

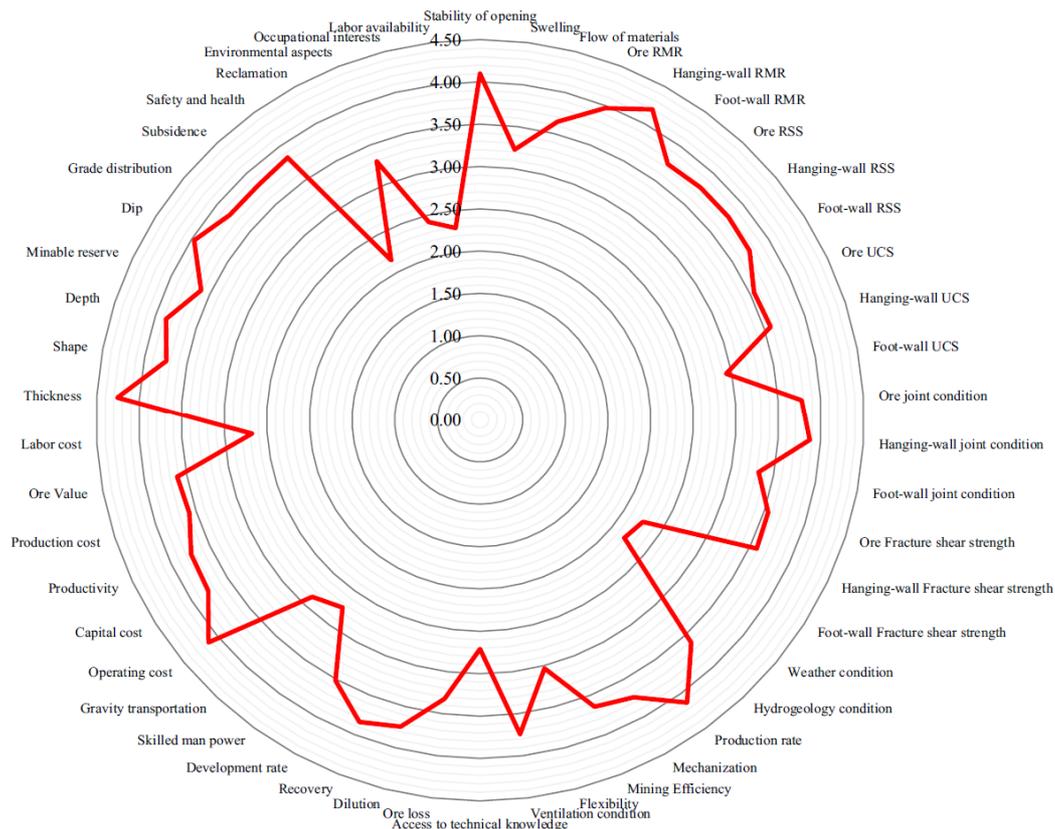


Figure 6 Typical example of the critical parameters considered in mining method selection in some of the most recent studies (adopted from Saki et al. 2020 with the permission of the authors)

Analysis of Figure 6 shows that experts have allocated the highest ratings to parameters such as the thickness of the orebody, rock mass rating of the hanging wall, and production rate from this comprehensive list. Biophysical impacts are probably implied in the single topic 'Environmental aspects'. It is implied that, still, the mining method selection based on experts' opinions is biased in favour of the geological and, to some extent, the geomechanical characteristics of ore bodies and the host rocks. It seems that this conventional point of view neither shows the value of post-mining land use nor incorporates the closure into the feasibility study of the mining method selection.

5 Expert survey on biophysical considerations

The results were extracted from a desktop study that was supplemented by workshops and interviews with experts identified from CRCTIME partner organisations. Due to limited opportunities to organise planned workshops at that stage of the COVID-19 pandemic, the data gathering was pivoted to a survey of experts who expressed interest. Experts included academics as well as industry and government representatives. To provide quantification of the outputs, the method of analysis is based on a matrix approach known as the AHP, proposed by Saaty (Saaty 1987, 2008), or the rock engineering system (RES) developed by Hudson at Imperial College London (Hudson 1992, 2017). The system has recently been used for an Abandoned Mine Instability Assessment Index (Salmi & Sellers 2022). The system's global response to any perturbation can be directly obtained from the mechanism's matrix. Once the interactions between parameters are identified, a detailed assessment of the most significant parameters can be conducted. The interconnections of the parameters are identified by judgement, usually from a panel of experts, and coded to develop the interaction matrix. The data in the interaction matrix can be used to assess the cause and effects, which show the impact and influence of parameters on each other.

In this survey, 22 experts from CRC TiME partner organisations were asked to rank each of the 16 parameters for impact assessment based on a 5-point scale from 0 (no impact) to 4 (critical impact). The research team selected the most common biophysical impact factors for the analyses. Due to the limited time and complexity of the pandemic, only 10 experts responded to the survey.

A sample of the results and analysis is presented here. Figure 7 shows the weighted average of the response for each biophysical impact for each mining method type. The data are coloured to show red as the highest rating and green where the impact is least. It appears that surface mining is considered to have the highest impacts, followed by underground and then in situ mining.

| Row Labels | InLine | InMine | InSitu | Open cast | Open pit | UG Cave | UG Longwall | UG Room & Pillar | UG Stope |
|--|--------|--------|--------|-----------|----------|---------|-------------|------------------|----------|
| Affecting the rate of erosion and weathering | 0.7 | 0.7 | 0.7 | 3.0 | 3.1 | 2.8 | 1.6 | 1.1 | 1.3 |
| Air pollution and dust problems | 0.7 | 0.7 | 0.7 | 3.0 | 2.9 | 1.3 | 0.9 | 0.9 | 0.9 |
| Biological effects | 1.0 | 1.0 | 1.0 | 2.8 | 2.5 | 1.5 | 1.3 | 1.0 | 1.0 |
| Capital costs | 2.3 | 2.5 | 2.3 | 3.2 | 3.3 | 3.0 | 3.0 | 3.0 | 3.0 |
| Effect on surface and subsurface aquifers | 2.7 | 2.7 | 2.7 | 3.3 | 3.3 | 2.5 | 2.5 | 2.4 | 2.4 |
| Effects on animals | 1.0 | 1.0 | 1.0 | 2.7 | 2.5 | 1.5 | 1.1 | 1.0 | 1.0 |
| Effects on indigenous land use | 1.7 | 1.7 | 1.7 | 3.1 | 3.3 | 2.3 | 1.8 | 1.4 | 1.4 |
| Effects on vegetation | 1.2 | 1.2 | 1.2 | 3.1 | 2.6 | 1.6 | 1.4 | 1.0 | 1.0 |
| Emissions | 1.1 | 1.4 | 1.3 | 3.3 | 3.3 | 1.8 | 1.5 | 1.5 | 1.5 |
| Hazards and effects on humans | 2.2 | 2.2 | 2.2 | 2.2 | 2.1 | 2.0 | 1.8 | 1.5 | 1.6 |
| Operating costs | 1.8 | 2.0 | 1.8 | 3.2 | 3.1 | 2.6 | 3.0 | 2.8 | 2.8 |
| Ore loss & not recovered | 2.2 | 1.8 | 2.0 | 2.3 | 2.0 | 1.6 | 2.0 | 3.0 | 2.0 |
| Rehabilitation costs | 2.0 | 2.0 | 2.2 | 3.3 | 2.7 | 3.0 | 2.0 | 1.6 | 2.2 |
| Size of tailing and tailing issues | 1.0 | 1.0 | 1.0 | 3.2 | 3.6 | 2.1 | 1.9 | 1.8 | 2.1 |
| Size of waste/spoil dumps | 1.0 | 1.0 | 1.0 | 3.0 | 3.4 | 1.8 | 1.6 | 1.4 | 1.9 |
| Slope instability issues and triggering landslides | 1.2 | 1.2 | 1.0 | 2.6 | 2.7 | 1.9 | 1.3 | 0.9 | 1.0 |
| SocioEconomic issues | 2.0 | 2.0 | 2.0 | 2.6 | 2.5 | 2.0 | 2.0 | 2.0 | 2.0 |
| Soil pollution | 0.7 | 0.7 | 0.7 | 2.2 | 1.9 | 0.9 | 0.8 | 0.8 | 0.8 |
| Surface subsidence and sinkholes | 2.5 | 2.2 | 2.3 | 1.1 | 1.2 | 3.1 | 2.5 | 1.3 | 1.5 |
| Water Pollution: Acid rock drainage | 2.5 | 2.8 | 2.8 | 3.3 | 3.4 | 2.9 | 2.6 | 2.4 | 2.8 |
| Water Pollution: Heavy metal contamination | | | | 3.1 | 3.3 | 2.4 | 2.3 | 2.3 | 2.4 |
| Water use | 2.3 | 2.5 | 2.7 | 3.5 | 3.6 | 1.8 | 2.2 | 1.8 | 2.0 |

Figure 7 Expert survey outcomes by average biophysical risk levels for the selected mining methods (red shading shows the highest average impact, with green being the least impactful – i.e. most favourable)

It is also interesting to consider where there is most disagreement by the experts. Figure 8 shows the standard deviation of the rankings. Again, red shading shows the biggest difference of opinion. The largest differences appear in cave mining and the novel in-place mining methods. With the underground methods, experts disagree on the impact of tailings and water pollution.

The novelty of the in-place mining methods means that there is little experience on which to base rankings. This observation is supported by the number of outcomes left unanswered, as shown in Figure 9. Most of the experts would be very familiar with surface mining methods, but less familiar with underground, especially around operating parameters such as water use, costs, and ore loss. Could this indicate differences in experience between closure practitioners and production engineers? Another interpretation of the lack of answers is that few professionals recognise the full extent of the biophysical impacts that mines create and need to be rehabilitated for closure. As production engineers with a long experience in operational issues (Sellers & Salmi 2020), considering the implications of production activities on closure outcomes during this project has been a fascinating learning journey.

| Row Labels | InLine | InMine | InSitu | Open cast | Open pit | UG Cave | UG Longwall | UG Room & Pillar | UG Stope |
|--|--------|--------|--------|-----------|----------|---------|-------------|------------------|----------|
| Affecting the rate of erosion and weathering | 0.76 | 0.76 | 0.76 | 1.00 | 0.99 | 1.58 | 0.92 | 0.83 | 0.89 |
| Air pollution and dust problems | 0.52 | 0.52 | 0.52 | 1.32 | 1.20 | 1.04 | 0.64 | 0.64 | 0.64 |
| Biological effects | 0.63 | 0.63 | 0.63 | 1.09 | 1.08 | 1.20 | 1.04 | 0.76 | 0.76 |
| Capital costs | 1.37 | 1.52 | 1.63 | 0.75 | 0.76 | 1.22 | 0.71 | 1.00 | 0.71 |
| Effect on surface and subsurface aquifers | 1.51 | 1.51 | 1.51 | 0.87 | 0.82 | 1.31 | 1.31 | 1.19 | 1.19 |
| Effects on animals | 1.10 | 1.10 | 1.10 | 0.71 | 0.85 | 1.20 | 0.83 | 0.76 | 0.76 |
| Effects on indigenous land use | 1.37 | 1.37 | 1.37 | 0.93 | 0.95 | 1.58 | 1.04 | 1.06 | 1.06 |
| Effects on vegetation | 0.98 | 0.98 | 0.98 | 0.78 | 1.07 | 0.92 | 0.74 | 0.76 | 0.76 |
| Emissions | 0.90 | 1.13 | 1.11 | 1.21 | 1.11 | 1.47 | 1.22 | 1.22 | 1.22 |
| Hazards and effects on humans | 1.60 | 1.60 | 1.60 | 1.09 | 1.10 | 1.51 | 1.28 | 1.31 | 1.19 |
| Operating costs | 1.33 | 1.26 | 1.33 | 0.75 | 0.90 | 1.34 | 1.00 | 1.30 | 1.10 |
| Ore loss & not recovered | 1.33 | 0.98 | 1.26 | 0.82 | 0.58 | 0.55 | 0.00 | 0.71 | 0.71 |
| Rehabilitation costs | 1.10 | 1.10 | 1.33 | 0.82 | 1.50 | 0.71 | 0.71 | 0.55 | 0.45 |
| Size of tailing and tailing issues | 0.89 | 0.89 | 0.89 | 0.67 | 0.70 | 1.64 | 1.64 | 1.67 | 1.64 |
| Size of waste/spoil dumps | 0.89 | 0.89 | 0.89 | 1.00 | 0.97 | 1.58 | 1.41 | 1.30 | 1.55 |
| Slope instability issues and triggering landslides | 0.98 | 0.98 | 0.89 | 1.01 | 1.06 | 1.36 | 1.04 | 0.99 | 1.07 |
| SocioEconomic issues | 1.55 | 1.55 | 1.55 | 0.88 | 0.85 | 1.41 | 1.41 | 1.41 | 1.41 |
| Soil pollution | 0.52 | 0.52 | 0.52 | 0.67 | 0.74 | 0.64 | 0.46 | 0.46 | 0.46 |
| Surface subsidence and sinkholes | 1.38 | 1.17 | 1.21 | 0.78 | 1.03 | 1.46 | 1.20 | 1.28 | 1.31 |
| Water Pollution: Acid rock drainage | 1.38 | 1.51 | 1.47 | 0.87 | 0.97 | 1.36 | 1.30 | 1.41 | 1.28 |
| Water Pollution: Heavy metal contamination | | | | 1.17 | 1.16 | 1.51 | 1.49 | 1.49 | 1.51 |
| Water use | 1.51 | 1.52 | 1.51 | 0.55 | 0.53 | 0.84 | 0.84 | 0.84 | 0.71 |

Figure 8 Expert survey outcomes by the standard deviation of biophysical risk for the selected mining methods (red shading indicates the highest disagreement on impact, with green having the least – i.e. more experts agree)

| Row Labels | InLine | InMine | InSitu | Open | Open pit | UG Cave | UG | UG Room | UG Stope |
|--|--------|--------|--------|------|----------|---------|-----|---------|----------|
| Affecting the rate of erosion and weathering | 30% | 30% | 30% | 10% | 0% | 20% | 20% | 20% | 20% |
| Air pollution and dust problems | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Biological effects | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Capital costs | 40% | 40% | 40% | 40% | 30% | 50% | 50% | 50% | 50% |
| Effect on surface and subsurface aquifers | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Effects on animals | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Effects on indigenous land use | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Effects on vegetation | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Emissions | 30% | 30% | 30% | 40% | 30% | 40% | 40% | 40% | 40% |
| Hazards and effects on humans | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Operating costs | 40% | 40% | 40% | 40% | 30% | 50% | 50% | 50% | 50% |
| Ore loss & not recovered | 40% | 40% | 40% | 40% | 30% | 50% | 50% | 50% | 50% |
| Rehabilitation costs | 40% | 40% | 40% | 40% | 30% | 50% | 50% | 50% | 50% |
| Size of tailing and tailing issues | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Size of waste/spoil dumps | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Slope instability issues and triggering landslides | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| SocioEconomic issues | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Soil pollution | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Surface subsidence and sinkholes | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Water Pollution: Acid rock drainage | 40% | 40% | 40% | 10% | 0% | 20% | 20% | 20% | 20% |
| Water Pollution: Heavy metal contamination | | | | 10% | 0% | 20% | 20% | 20% | 20% |
| Water use | 40% | 40% | 40% | 40% | 30% | 50% | 50% | 50% | 50% |

Figure 9 Expert survey outcomes left unanswered for the selected mining methods (red shading indicates the highest unanswered, with green having the most answered)

Finally, it would be remiss not to rank the perceived biophysical impacts and the mining methods. One way would be to sort on the average impact, as shown in Figure 7. Averaging does not consider the items where most people have a concern. To do this, one ranking approach is to consider the percentage of people rating the impact as strong or critical (top two out of five). The rankings produced by this method are shown in Table 2. These rankings indicate that various aspects of water pollution are highest in people's minds. The experts have rated surface mining and caving as the three mining methods with the highest impact. This is not surprising as they have the highest productivity, affect the largest surface area, and produce the most waste. The higher rating for impact on water is probably why the in-situ mining methods involving leaching are rated as having a higher impact than selective mining.

These factors are a combination of biophysical, ecological, and socio-economic factors. In the definition of quantified value-created process, Stacey & Hadjigeorgiou (2022) noted that the use of short-term costs in feasibility study for decision-making may not properly show the real value and the ESG opportunities that are generated. The use of capital costs, and operational costs, in this survey does not help to find the right mining method for generating the best long-term value. However, when these factors are combined with the other biophysical factors (for risk and opportunity assessment) as well as other socio-economic factors, then the real value created in the entire mining value chain and the subsequent closure and post-mining phases can be quantified and captured.

Table 2 Rankings of biophysical and socio-economic impacts and mining methods by considering the percentage of respondents ranking the top two criteria (strong and critical impact)

| Rank | Biophysical impact | Mining method |
|------|--|--------------------|
| 1 | Water pollution: Heavy metal contamination | Open pit |
| 2 | Water pollution: Acid rock drainage | Open cast |
| 3 | Effect on surface and subsurface aquifers | UG cave |
| 4 | Capital costs | UG longwall |
| 5 | Size of tailing and tailing issues | In-mine |
| 6 | Water use | UG stope |
| 7 | Surface subsidence and sinkholes | In situ |
| 8 | Effects on Indigenous land use | UG room and pillar |
| 9 | Operating costs | Inline |
| 10 | Socio-economic issues | |
| 11 | Size of waste/spoil dumps | |
| 12 | Affecting the rate of erosion and weathering | |
| 13 | Hazards and effects on humans | |
| 14 | Rehabilitation costs | |
| 15 | Emissions | |
| 16 | Effects on vegetation | |
| 17 | Slope instability issues and triggering landslides | |
| 18 | Effects on animals | |
| 19 | Air pollution and dust problems | |
| 20 | Biological effects | |
| 21 | Ore loss and not recovered | |
| 22 | Soil pollution | |

6 Discussions and conclusions

The paper considers the effect of the mining method on the biophysical impacts of mining and the difficulties implied by mine closure. The study highlights the current problems, identifies transformational opportunities, and presents future mining methods with improved closure outcomes. The findings also show that the new mining methods can modify the closure issues relative to conventional mining methods, which often require large open pits, voids underground, and large tailings footprints. The novel methods are anticipated to reduce closure risks but could even increase risks when using new technology with real or perceived challenges. The survey highlighted that many experts have focused understanding, perhaps with implicit assumptions, of the biophysical aspects of specific mining methods, implying that there are silos of understanding between methods and across the range of biophysical impacts that need to be deconstructed

to achieve improved closure outcomes. More interaction is needed for the industry to have a broader perspective of the relative impact of issues across all mining methods.

Even though the survey was conducted with a limited sample, it provided a considerable amount of information to evaluate. It is considered that the survey shows that alternative mining methods appear to have lower risk perception, although higher unknowns. The survey outcomes resulted in a discussion on how to increase the recognition and knowledge of biophysical impacts from different mining methods for different professional groups across the mining value chain or focused on specific mining methods. A workshop on how to put this concept into practice provided ideas such as simulations, trials, small initiatives, breaking into separate projects, and economic studies, and suggestions to identify potential candidate mines that would be keen to engage. Future biophysical impacts should also be addressed during targeting and exploration in feasibility studies, like the consideration of geopolitical conditions. Such research would be beneficial to reducing the silos of understanding closure across different mining methods and determining how a consistent quantification of biophysical risk could be developed.

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