

**Review**

## **The criteria for ranking and prioritization of rehabilitation of abandoned mines**

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### **Abstract**

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The rehabilitation of abandoned mines begins with the characterization and ranking of these mines. Based on this, countries, organizations, and individual researchers have developed tools for ranking abandoned mines for rehabilitation. This paper comments on the issues of abandoned mines which include their definition and the problems they possess. It then critically examines the criteria used by different tools to prioritize the rehabilitation of abandoned mines. It showed that there is a sharp increase in the number of academic tools developed for the ranking of abandoned mines over the years. These tools demonstrated how the parameters disregarded in official ranking tools can rank the abandoned mines for rehabilitation. The paper recommends that the main issues of abandoned mines and their rehabilitation be part of the criteria of ranking these mines for rehabilitation. The inclusion of such parameters in the ranking criteria promises to improve the accuracy of the ranking process. It will go a long way in ensuring that the ranking tools provide the correct advice on what strategies can be used to rehabilitate these mines.

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## **Introduction**

Abandoned mines are in different parts of the world. They are common in regions that have a long history of mining. They are known to be the product of previous poor mining practices that had no regard for the environment, the potential risk to human and social demotion (Kivinen, 2017). According to MMSD (2002), these mines present a period where mining had no care and planning, and some regulations were inadequate. Although this is the case, there are several reasons behind premature closure and subsequent abandonment of the mine. These reasons can be geological, economic, technical, political, regulatory, and small-scale mining (Mackasey, 2000; MMSD, 2002; Lourence, 2006). In general, abandoned mines have different forms of environmental problems and

health and safety hazards. These problems negatively affect the socio-economics of the abandoned mine's host communities (Garavan et al., 2008; Mhlongo and Amphonsah-Dacosta, 2015). These problems may worsen, remain the same or reduce with time (Mhlongo et al. 2020). Regardless of the situation, abandoned mines need rehabilitation or reclamation to reduce or eliminate their hazards and make the land they occupy available for other uses. As a result, programs of rehabilitating abandoned mines were initiated in almost all countries (e.g., South Africa, Australia, Canada, Namibia, Chile, UK, and the USA) where there are large numbers of abandoned mines. Their rehabilitation is generally the responsibility of the government. Because of this, projects of rehabilitating abandoned mines suffer from a lack of

resources. This makes the rehabilitation of abandoned mines first consider protecting the safety and health of the citizens (MMSD, 2002). Ranking and prioritizing the abandoned mines is an integral part of the program of rehabilitation of these mines. It aims to ensure that the rehabilitation is systematic to allow easy monitoring of future works in the sites. It also assists with focusing the future remediation or rehabilitation activities (Atanackovic et al., 2016). However, the accuracy of prioritizing abandoned mines for rehabilitation also depends on the robustness and inclusivity of the ranking model or tool used. The main aim of this paper is to systematically review the criteria used by existing tools for prioritizing the rehabilitation of abandoned mine sites.

### Abandoned Mines and the Overview of Their Problems

It is a fact that there is no universal definition for abandoned mines. These mines are defined differently

from one region or country to the other. The differences in the definitions of abandoned mines somehow determine how these mines are identified and managed in different areas. According to Hogan and Tremblay (2006), the definition of abandoned mines should be more descriptive to be relevant to the database and bring clarity and meaning to these mines. These mines exist under different names that include derelict, ownerless, orphaned mines, and mining liability as defined in Table 1 (Tremblay and Hogan, 2006; Garavan et al., 2008; Renner et al., 2009).

These definitions of abandoned mines are phrased around the issues of ownership, responsibilities of rehabilitation, impact or risks they possess, the need for rehabilitating them, and their features. Outside the definition, these mines have features that present varying degrees of problems (i.e., environmental and physical hazards) (Liu et al., 2012; Mhlongo et al., 2020). The problems of these mines depend on their (i) location, (i) nature of the deposit mined, and (ii) the scale of the mining operation.

Table 1. The terms and definitions of abandoned mines used in different counties.

Term	Definition	Source
Ownerless mines	<ul style="list-style-type: none"> <li>▪ Mine sites where the owner has ceased or indefinitely suspended advanced exploration, mining, or mine production without rehabilitating the site.</li> </ul>	Castrilli (2010)
Derelict and ownerless mines	<ul style="list-style-type: none"> <li>▪ Mines whose owners or mining rights or lease holders have abandoned and are not operating nor maintaining to mitigate and manage their safety, health and environmental impacts and can no longer be traced.</li> </ul>	DMR (2009)
Orphaned mines	<ul style="list-style-type: none"> <li>▪ Are those mines for which the owner cannot be found or for which the owner is financially unable or unwilling to carry out clean-up.</li> </ul>	Garavan et al. (2008)
Mining liability	<ul style="list-style-type: none"> <li>▪ An abandoned mine or part of it that produces a significant risk to health and safety.</li> </ul>	Renner et al. (2009)
Abandoned mine land	<ul style="list-style-type: none"> <li>▪ Those lands, waters and surrounding watersheds where extraction, beneficiation or processing of ores and minerals has occurred.</li> </ul>	USEPA (2021)*

\*<https://www.epa.gov/superfund/abandoned-mine-lands>.

In general, abandoned mines have features such as:

- Surface pits,
- The different types of mine entries,
- Large heaps of mine waste dams (i.e., tailings, spoils, and waste rock dams),
- Dilapidated buildings,
- Abandoned pieces of machinery and
- Others such as mine subsidence and sinkholes.

These features can be associated with environmental problems, health risks, and safety risks that have a magnitude that varies from one site to the other, one commodity to the other, and from one mining method to the other. The problems of abandoned mines have an impact on the socio-economic status of the nearby and host communities. For example, the high physical and environmental hazards of abandoned mines may

increase the socio-economic concerns of these mines. The goals of rehabilitation of these mines are to address their physical and environmental risks. They should also alleviate some of the socio-economic issues that prevail in the communities found around these mines.

The environmental problems of the abandoned mines can be physical land degradation or environmental pollution. In this context, the concept of land degradation refers to the negative trends in land condition caused by abandoned and unrehabilitated mines in the biophysical environment. Environmental pollution is the contamination of the biophysical environment by substances from the abandoned mine site. Land degradation and pollution affect the livelihoods and the health and safety of people (Zorn and Komac, 2013; Jan et al., 2016; Landrigan et al.,

2018). Physical land degradation issues of mining (including abandoned mines) include landscape alteration because of extensive surface excavations and heaps of mine waste dumps. They include the development of ground subsidence (that takes the form of sinkholes) and the burning of remnants of coal in discards and underground mine workings (Jan et al., 2016; Landrigan et al., 2018). Some are soil structure alteration, change in vegetation cover, and change of both surface and groundwater regimes (UNEP and COCHILCO, 2001). Litter of the landscape with objects such as empty containers and scrap metals is also a common physical environmental problem in abandoned mines (Mhlongo et al., 2019).

Environmental pollution is one of the universal problems which is also associated with abandoned mine sites. The soils in some parts of these mines, including areas around the waste dumps (especially the tailings and waste rock dumps) and mine-water discharge, mostly have a high concentration of heavy metals such as Zn, As, Cu, Cd, Ni, Fe, and Se (El Amari et al., 2014; Fashola et al., 2016; Ngole-Jeme and Fantke, 2017). The erosion of soil and tailings and discharge of drainage from abandoned mine sites contribute to the contamination of river sediments and aquatic ecosystems (Bini, 2011). Air pollution by dust from old tailings is one of the health-threatening problems of abandoned mines (Del Rio-Sales et al., 2019; Entwistle et al., 2019).

In general, environmental pollution (including that which is due to abandoned mining sites) contributes significantly to the death (~9 million, Landrigan et al., 2018) of people due to different health problems. Contamination from the abandoned mines might also contribute to people developing cancer-related diseases and respiratory conditions (e.g., cough, asthma, wheezing, and chest cold). They can also suffer diseases such as silicosis, asbestosis, and pneumoconiosis (Olufeni et al., 2018). Environmental pollution by abandoned mine site also affects animals and the economic development of the area. For example, pollution from abandoned coal mines affected the water drunk by cattle in the Mpumalanga Province of South Africa. This affected milk production and quality in the area (Olufeni et al., 2018). Consequently, the economic status of the dairies and the surrounding communities were considerably affected.

These mines also have serious public safety hazards. They also affect the aesthetic appearance of the landscape. These problems turn to reduce the quality of the land around the abandoned mine sites. For example, ground subsidence and high walls of abandoned surface mine excavations can result in injuries or death. The safety risk of sinkholes that develops because of ground subsidence in historic underground mine workings is one of the safety risks of abandoned mines. These risks are worsened by that the upper (cone-shaped) part of the sinkholes is made up of loose material that crumbles and gravitates

people and animals who enter such a cone into the deeper part of the sinkhole. According to Tsolaki-Fiak et al. (2018) and Misthos et al. (2019), abandoned surface mine excavations like those of the quarries appear with contrasting colors in the landscape. Such reduces the aesthetic of the landscape. It also results in the deterioration of the scenic quality of the area. Thus, affecting the tourism sector in the areas as the damages by mining on the landscape presents a very negative view to tourists and other people who are not from within the mining community (Dentoni et al. 2006).

To address all these problems of abandoned mine sites, their rehabilitation is mandatory. The work of rehabilitating these mines in different countries is generally the government's responsibility. Rehabilitating these mines requires that their hazards get assessed and the magnitude of such hazards quantified. The assessment of abandoned mine sites also helps with the ranking of these mine for rehabilitation. Because the governments of many countries do not have sufficient resources required to rehabilitate all abandoned mines at once, they have developed and adopted ranking tools that prioritize the rehabilitation of these mines.

In this paper, these abandoned mine ranking tools are classified as academic or official tools. In this case, the tools developed and used officially to rank abandoned mines in a country are official tools, while those developed and used by individual researchers are academic tools. The ranking criteria of these tools were analyzed to establish their unique features. The information gathered about these tools included the year they were including the area or country they were applied to, and their ranking parameters (see Table 2).

## Ranking and Prioritization of Abandoned Mines

The program of abandoned mine's rehabilitation commences with the identification and location of these mines and their features using different appropriate techniques. For example, ground survey, geophysical methods, and remote sensing techniques have been used to locate hidden abandoned underground mine shafts around the abandoned mine lands (Gallager et al., 1978; Gunn et al., 2006; Chambers et al., 2007; Mhlongo et al., 2018). Locating these sites is then followed by their characterization to develop an inventory of abandoned mines in the country or region. Different tools were developed and are used to identify, define and quantify the problems of these mines. They also help to screen and rank these mines for rehabilitation. According to Al-Sharrah et al. (2016), the ranking of abandoned mines using either relative or categorized ranking tools helps to focus the attention and resources on the mines or parts of the mines that present higher risks. These tools are also expected to provide information that helps choose the best methods for rehabilitating the abandoned mine sites.

Table 2. The summary of the ranking criteria used by the existing abandoned mines ranking tools.

No	Reference	Type of site or feature	Category	Ranking parameters									
				PLD	PE	HR	SR	SC	EI	VI	RF	LU	D
1	Environmental Protection Agency (1990)	Not specific	Official Tool		√	√	√						
2	Day and Harpley (1992)	Not specific	Official Tool		√								√
3	USEPA (1992)	Not specific	Official Tool		√	√	√						
4	Duszak et al. (1993)	Not specific	Official Tool	√	√	√	√	√				√	
5	Pioneer Technical Services (1996)	Reclaimed Mine	Official Tool		√	√	√						
6	Shevenell et al. (1997)	Not specific	Official Tool		√	√	√						
7	Rankin et al. (2007)	Not specific	Official Tool		√	√	√						
8	Mayes et al. (2009)	Non-coal mines	Official Tool		√			√	√				
9	van Rensburg et al. (2009)	Asbestos waste	Academic Tool	√	√		√			√			
10	Power et al. (2009)	Not specific	Official Tool		√	√							
11	PGeo et al. (2009)	Not specific	Official Tool		√	√							
12	Renner et al. (2009)	Not specific	Official Tool		√	√	√						
13	Ndalulilwa et al. (2011)	Not specific	Official Tool		√		√						
14	Jarvis and Mayes (2012)	Non-coal mines	Official Tool		√						√		√
15	Abdaal et al. (2013)	Mine waste	Academic Tool		√	√							
16	Mhlongo et al. (2013)	Not specific	Academic Tool		√	√	√						
17	Jordan and Abdaal (2013)	Not specific	Academic Tool		√			√	√		√		
18	Rapson (2014)	Coal Mines	Academic Tool	√	√	√	√	√	√				
19	Caravanos et al. (2014)	Not specific	Academic Tool		√			√	√				
20	Kubit et al. (2015)	Not specific	Academic Tool	√	√		√						
21	Atanacković et al. (2016)	Not specific	Academic Tool		√								
22	Kim et al. (2016)	Not specific	Academic Tool		√								
23	Shilling et al. (2017)	Not specific	Official Tool		√	√	√						
24	Mavrommatis and Menegaki (2017)	Quarries	Academic Tool	√						√			
25	Zhang et al. (2018)	Not specific	Academic Tool	√									
26	Mhlongo et al. (2018)	Mine shafts	Academic Tool		√	√	√	√	√				
27	Ahmed and Oruonye (2018)	All and quarries	Academic Tool		√	√	√						
28	Mhlongo et al. (2019)	Tailing dams	Academic Tool	√	√	√	√			√			
29	Mitchell et al. (2019)	Not specific	Official Tool		√		√						
30	Cornelissen et al. (2019)	Asbestos mines	Official Tool		√	√	√					√	

Note: PLD is physical landscape degradation, PE is pollution of the environmental, HR is health risk, SR is safety risk, SC is social concerns, EI is economic issues, VI is visual impact, RF is regulatory framework, LU is land utility, and D is the type of the deposit.

The development of an inventory of abandoned mine sites follows the criteria of the adopted method of ranking these mines for rehabilitation. Thus, the amount of data required by the abandoned mines prioritization tools determine how easy it will be to use such a tool in other countries. This is because sometimes the data needed by some tools are expensive to generate, thus making the characterization and ranking of abandoned mines in other countries not affordable. According to Kubit et al. (2015), this is one factor that made the adoption and use of some of the existing tools in developing countries difficult or impossible. Also, what limits the application of the existing tools in other countries is that they do not consider all the impotent aspects of abandoned mines and their rehabilitation in the ranking criteria. For this work, a total of 30 abandoned mines ranking tools published between 1990 and 2019 were identified and analyzed.

About 16 (53.3% of the total) were classified as official tools, while 14 (46.7% of the total) were academic tools. Figure 1a shows the actual and cumulative publications of the abandoned mines ranking tools identified between 1990-2019. Figure 1b shows a sharp increase in the ranking tools developed during the year 2000 to 2019. The quest to address the limitations of the official tools is a possible reason for an increase in the number of new and modified tools developed and published between 2009 and 2019. The shortcomings of the official tools that affect their accuracy and application in developing countries were identified by Caravanos et al. (2014) and Kubit et al. (2015). These limitations are in Table 3, supported the argument made by these authors is the fact that most of the official tools that were analyzed in this study were developed and used in countries classified as developed economies (United Nations, 2020) (See Table 4).

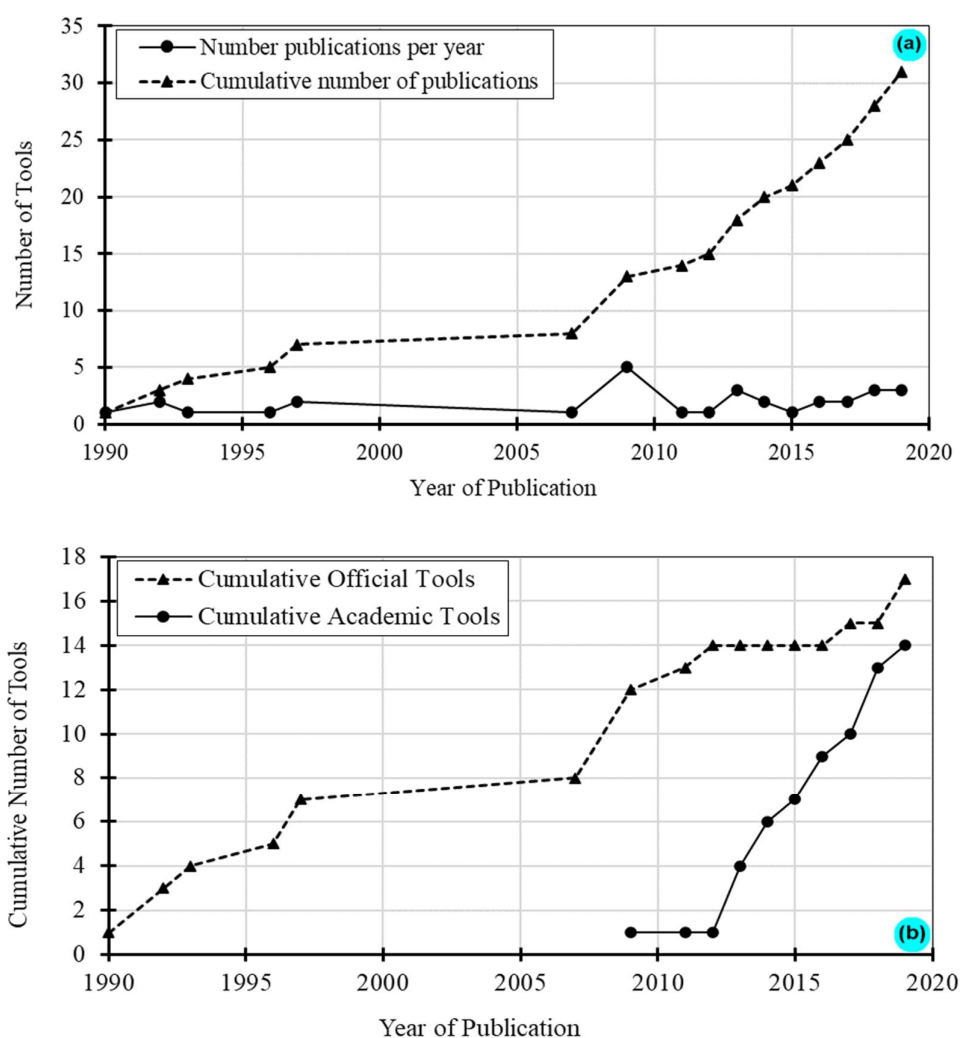


Figure 1. (a) The actual and cumulative number of publications abandoned mines ranking systems per year, and (b) Cumulative number of published official and academic tools published between 1990 and 2019.

Table 3. The disadvantages of the established official tools that affect their accuracy and limits their application in developing countries.

Affected aspect	Disadvantages	Reference
Application in developing economy countries	<ul style="list-style-type: none"> <li>▪ Developing countries lack the required infrastructure and financial capacity to conduct the extensive and complex studies needed by these tools.</li> <li>▪ Developing countries have relatively high number of abandoned mine that continually pollute the environment as their characterization is taking too long to complete</li> <li>▪ The cost of hazard ranking system using these tools are generally very high for developing countries</li> <li>▪ Most of the prerequisite data that is needed by these methods is generally not available in developing countries.</li> </ul>	Caravanos et al. (2014)
Accuracy and usefulness	<ul style="list-style-type: none"> <li>▪ Lack of transparency with regards to the ranking algorithms they use and the rational basis for selecting weighting factors.</li> <li>▪ These tools use too general parameters and disregard some of the important parameters for ranking abandoned mines.</li> <li>▪ *They provide guidance on limited number of reclamation methods to be considered.</li> </ul>	Kubit et al. (2015)

Note: \*Many of these tools are not capable of suggesting rehabilitation strategies to be considered.

Table 4. The distribution of the documented ranking tools across the developing and developed economy countries.

Tool type	Number of Countries		Number of Developed Tools	
	Developing economy	Developed economy	Developing economy	Developed economy
Official Tool	4	11	4	12
Academic Tool	5	3	10	4
Total	9	14	14	16

### The Analysis of the Ranking Criteria

The abandoned mines ranking tools use defined criteria to generate scores that rank and prioritize abandoned mines for rehabilitation. Figure 2a shows that environmental pollution and safety and health risks are the parameters used by many tools for ranking abandoned mines. However, the parameter that is commonly used by official ranking tools is the safety risk. It is then followed by the health risks and physical land degradation (see Figure 2b). Because of this, the programs of rehabilitating the abandoned mines in most countries focus on protecting the safety and health of people and animals. This is followed by cleaning up the environment to eliminate the health risks associated with contaminated industrial sites (including mining). Prioritizing the protection of health and safety issues in the rehabilitation program is influenced by that money for rehabilitating the abandoned mines is from the government (MMSD, 2002).

The academic tools used physical land degradation, and at almost the same level, environmental pollution and health risks. The other parameters used more in academic tools are the socio-economic issues and the visual impacts caused by the main features of abandoned mines. In a country like

South Africa, the socio-economic issues are demonstrated by a widespread illegal and artisanal mining activities in abandoned mine sites, mushrooming of informal settlements in abandoned mine lands, and reducing living standard in abandoned mines host communities (Limpitlaw and Briel, 2014; Mhlongo and Akintola, 2021). According to Cornelissen et al. (2019), the official ranking tool used in South Africa considers these issues of abandoned mines under the parameter called “land utility”.

In the ranking tools analyzed in this work only six tools considered socio-economic issues in their ranking criteria. Two of them are official tools reported by Duszk et al. (1993) and Mayes et al. (2009). The other four are academic tools developed and reported by Jordan and Abdaal (2013), Rapson (2014), Caravanos et al. (2014), and Mhlongo et al. (2018). The visual impact parameter has been not used in official tools. However, they have been used in academic tools to describe the impact of the mine features on the appearance of the landscape. As a result, some tools use the term “visual impact” (Mavrommatis and Menegaki, 2017; Mhlongo et al., 2019), while others use “aesthetics” to refer to this parameter (van Rensburg et al. 2009). It has been used to rank large and prominent abandoned mine features such as abandoned excavations and tailings.

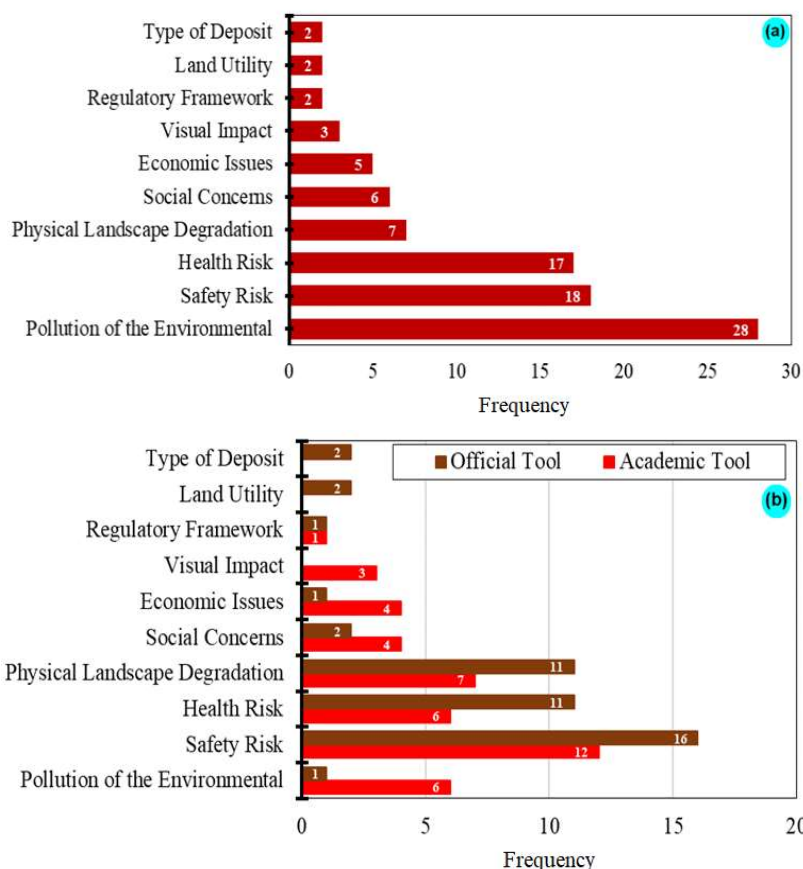


Figure 2. The frequency which the ranking parameters have been used in the ranking of abandoned mines. (a) show a general situation, while (b) compares between official and academic tools.

Safety risks and environmental problems have been widely used in ranking and prioritization of abandoned mines for rehabilitation. Noticeable, the risks of ground subsidence associated with abandoned mines have not been directly used to rank these mines. Post-mining subsidence is a serious safety risk, especial in urban areas developed above the abandoned mine workings (Salmi et al., 2019). They are also environmental problems that affect the usability of the land above the mine workings (Bell et al., 2000). The fact that post-mining subsidence is a complex problem and difficult to quantify is possible the main reason for the limited use of subsidence as a parameter in the criteria of ranking these mines. Moreover, in developing countries, the information and data needed to quantify post-mining subsidence are not always available. Such include information about the used mining method, the maps of the labyrinth of abandoned underground tunnels, and the size, shape and location of the pillars and stopes.

The other important ranking parameter that is commonly disregarded in the criteria of ranking the abandoned mine sites for rehabilitation is post-mining uses of the mine features or the site. Identifying post-mining land use helps in setting the objectives and/or

goals of rehabilitation. It also assists in ensuring that the post-mining land uses and the geophysical and morphological characteristics of the rehabilitated mine site are compatible with the surrounding areas (Narrei and Osonloo, 2011). The work by Zhang et al. (2018) demonstrates the importance of post-mining land use planning and how it possible uses in prioritizing the rehabilitation of abandoned mine sites.

The difficulty of quantifying some of the problems (e.g., socio-economic issues) of abandoned mines limits their uses as the criteria for ranking these mines. Determining some of the parameters of ranking abandoned mines is also time-consuming and expensive. The use of such parameters in prioritizing the rehabilitation of abandoned mines makes their characterization extensive and expansive. This situation can be very problematic in developing countries with many abandoned mines and limited resources for rehabilitating them (Mhlongo et al., 2018). Therefore, the ranking tools must accommodate both qualitative and quantitative aspects of abandoned mines in the ranking of these mines for rehabilitation. The ranking criteria should also ensure that the priority of rehabilitating these mines is done within the shortest possible time.

## Conclusion

The ranking and prioritization of abandoned mines should holistically take into consideration the main issues of abandoned mines and their rehabilitation. The ranking parameters should be chosen and used in a way that makes the ranking tool or criteria user-friendly and robust enough to produce reliable and accurate results. Efforts to incorporate parameters such as socio-economic issues, risks of post-mining subsidence, and issues of post-mining land uses into the criteria of ranking these mines should be made. The use of previously disregarded parameters in official tools will improve the accuracy of these tools. It will also go a long way into upgrading “abandoned mines ranking and prioritization tools” to “abandoned mines rehabilitation management tools” capable of setting rehabilitation goals while helping to select appropriate rehabilitation strategies for the abandoned mine sites.

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