Development and use of hazard ranking system for abandoned mine entries: A case study of the mine shafts in Giyani and Musina areas of South Africa

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Abstract: Treatment of old mine shafts can be a tedious and costly process if not carefully planned and managed. This paper presents the work conducted with the aim of evaluating the risk of abandoned mine shafts in the Giyani and Musina areas to guide the work of their treatment. The method that allowed the ranking of physical and environmental hazards of the shafts together with their corresponding socio-economic concerns was developed and applied in this work. The results showed that the risks of falling into the shafts and the problems of ground movement were the major physical hazards and environmental stresses of the shafts. Based on the results of the study, it was concluded that in addressing the problems of abandoned mine shafts, priority should be given to mitigation strategies for the major hazards followed by those that prevent release of toxic gases and discharge of contaminated mine water by the shafts. The method used in this work is recommended for preliminary evaluation of the hazards of abandoned mines in developing countries which have many abandoned mine sites and limited resources to conduct their rehabilitation.

Keywords: abandoned shafts; hazard ranking; public safety; South Africa

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PUBLIC INTEREST STATEMENT

Abandoned mine features like underground entries present different types and degree of physical and environmental hazards as well as socio-economic concerns. The aim of this work was to develop a methodological and less data demanding but robust system for ranking the hazards of abandoned mine entries. The use of such method in abandoned shafts in the areas of Giyani and Musina (South Africa) allowed that the issues of these shafts are ranked. In addition, the developed system showed potential of changing site characterization and rehabilitation work for abandoned mine entries in developing countries like South Africa.
1. Introduction

Mine entries are common features of abandoned mine sites where mineral exploitation made use of underground mining methods. They are generally characterized by risks of accidentally falling into old mine workings. This may lead to death due to physical body injuries, drowning in water filling the workings, suffocation due to lack of oxygen and exposure to toxic mine gases (Holmes, 2008; Salmon & Degas, 2003; Wrona, Rozanski, Pach, Suponik, & Popczyk, 2016). Exacerbating the safety risks of the mine shafts is that they are commonly found at deplorable state, untreated or treated with temporal structures which easily collapse when there are minor ground movements (Chambers et al., 2007). It is important to note that even treatment strategies that are considered permanent do collapse after a long time of installation thus increasing the safety risks of the shafts (Culshaw, McCann, & Donnelly, 2000; Wrona et al., 2016).

Although the dangerous nature of abandoned mine shafts and other entries appear to be obvious, in South Africa and other developing countries with large number of abandoned mine sites, fatalities and nature of accidents occurring in these shafts are not known with certainty. According to illegal gold miners (also known as Zama-Zamas) who go underground through old shafts in the Witwatersrand Basin, at least every week one person dies in abandoned mine shafts in South Africa (Sieff, 2016). Under reporting of accidents and fatalities occurring in abandoned mine sites was explained by Skinner and Beckett (1994) because of no existence of formal reporting channels of such accidents in many countries or regions.

After recognizing the safety threats of abandoned mine shafts in South Africa, the government together with communities tried using different strategies to treat these shafts with the purpose of eliminating their physical hazards. The dilemma with this approach is that the treatment of the shafts is often done without any systematic evaluation of physical hazards, environmental problems and socio-economic concerns of the shafts. Such lack of basic understanding of the issues of abandoned mine shafts led to the use of inappropriate treatment options which easily collapse or get removed after installation thus failing to fulfil the purpose of the treatment. In view of this, the work presented in this paper was conducted with the purpose of creating an understanding of the problems of abandoned mine shafts in the Giyani and Musina areas while prioritizing their treatment. To achieve this, a robust and less data demanding method for preliminary ranking of the hazards of the shafts was developed and applied.

In general, the identification, description and ranking of the hazards of abandoned mines is an integral part of the programme of rehabilitation of these sites (Greeley, 1999). Based on this and other reasons, there has been an increase in studies aimed at developing tools for prioritization of rehabilitation of abandoned mine sites. Different authors (e.g. Kubit, Pluhar, & De Graff, 2015; Mavrommats & Menegaki, 2017; Mhlongo, Amponsah-Dacosta, & Mphephu, 2013) and organizations have developed and applied different decision-making tools for rehabilitation of abandoned mine sites. Some of the most popular tools used in different parts of the world to prioritize the work of rehabilitation of abandoned mine site are presented in Table 1. Some of the challenges of adopting these tools outside the context they were developed have been reported in Kubit et al. (2015) and Mavrommats and Menegaki (2017) and they include lack of transparency, leave out important parameters and reclamation methods, lack of model calibration and are at times data-demanding and time consuming. To overcome these challenges, it is important that assessment and hazard ranking tools that are less data-demanding, methodological and easy to apply in different situations of abandoned mines are developed. In view of this, the method used for preliminary assessment of abandoned mine entries in this work was developed.

2. Methodology

The ranking approach used in this study was developed by modification of the methodology of the Historic Mine Site Scoring System (HMS-SS) which was used to rank historic mine sites in Ireland. The HMS-SS prioritizes the rehabilitation of abandoned mines based on effect of the contaminated mining site on the environment and the safety and health of people and animals. It used the
source, pathway and receptor paradigm to rank abandoned mining sites with the aim of prioritizing their rehabilitation. The use of this approach in measuring the seriousness of the risks or hazards of mine features such as abandoned shafts, derelict buildings and disused surface excavations requires that the method is modified to suit the specific problems. In view of this, the method was extensively modified to allow the preliminary ranking of the mine shafts based on

| System | Description | Source |
|--------|-------------|--------|
| Abandoned and inactive mines scoring systems | ● Was used to rank abandoned and inactive mine sites in Montana  
● Developed based on the CERCLA-HRS*  
● The data used were physically collected at each site to assign the rank scores  
● It can evaluate potential safety hazards of the abandoned mine sites | Pioneer Technical Services (1994); Jordan and Abdaal (2013) |
| Reclaimed abandoned and inactive mines scoring system | ● Was used to estimate the risks of reclaimed abandoned mine sites in Montana  
● It was developed based on the principles of the AIMSS | Pioneer Technical Services (1994) |
| ARD potential based ranking of abandoned mines | ● Was used in ranking abandoned mine sites based on ARD potential in BC  
● It used information about mineral occurrences and that provided by government officials to rank the sites  
● The ranking is mainly based on environmental issues of the sites | Day and Harpley (1992) |
| RRM | ● Was used in ranking abandoned mines in BC  
● Ranking was done/conducted based on PSI of risk of abandoned mine sites  
● It considered both human health and environmental impacts in the ranking | Power et al. (2009); Tremblay and Hogan (2009) |
| Historic mine sites inventory and risk classification scoring system | ● Was used in the ranking of abandoned mines in Ireland  
● Developed with significant modification of the AIMSS  
● Ranked abandoned mine sites based on their impact on human health, animal health and the environment | Luodes (2013); Geological Survey of Ireland and the Environmental Protection Agency, n.d.; PGeo et al. (2009) |
| Abandoned mines hazard rating system | ● Was used in ranking abandoned mines in Ontario (Canada)  
● It was the first computer-based expert system for ranking abandoned mines  
● It considered factors such as public safety, public health, environmental problems, social concerns and economic issues in the ranking | Bolger et al. (1995); Mackasey (2000) |
| Preliminary appraisal and ranking model | ● It is a system comprising two components for ranking the physical and chemical hazards  
● It was used extensively in the ranking of abandoned mine sites in California | Kubit et al. (2015) |

*Note: CERCLA-HRS: Comprehensive environmental response, compensation and liability act-hazard ranking system; BC: British Columbia; RRM: risk ranking methodology.
their major public safety and health, environmental problems and socio-economic impacts. It involved carrying out a preliminary characterization of the shafts, scoring and ranking of their potential physical and environmental hazards as well as their socio-economic impacts. The flow of the activities involved in the methodology used in this work is shown in Figure 1.

2.1. Field characterization of the mine shafts

The characterization of abandoned mine shafts commenced with locating the shafts. In general, the detection or location of historic and abandoned mine shafts can be a challenging task, depending on the age and availability of historic data about the abandoned mine site. Depending on conditions that prevail at abandoned mine sites, techniques such as ground survey, drilling and trenching, remote sensing and geophysical methods have been used to locate historic mine shafts (Chambers et al., 2007; Gallagher, Henshaw, Money, & Tarling, 1978; Gunn et al., 2006). The limitations of the use of geophysical techniques have been explained by Gunn et al. (2006) and Chambers et al. (2007) to be the lack of confidence on the methods as they have not always yielded positive results and that it is still not clear which geophysical method is the most suitable for this purpose. On the other hand, ground survey and drilling and trenching approaches are generally considered time consuming, expensive and not safe, while remote sensing turn to have too many restrictions (Gallagher et al., 1978; Gunn et al., 2006).

In the case of this work, the mine shafts were located using ground survey method which involved traversing around the abandoned mine sites to locate the shafts and describe their current state, uses and potential physical and environmental hazards. Guidance by local people, former employees of the mines and artisanal miners who work around the abandoned mining sites assisted in locating the most hidden shafts. This approach of locating abandoned mine shafts was employed since most shafts in the Giyani and Musina areas are found in relatively densely vegetated areas and are without some of the structures such as headframe that can aid in their identification.

2.2. Scoring of hazards

Based on the results of preliminary field characterization of the shafts, their environmental and physical hazards were quantified using a scoring and ranking technique. This involved assigning numerical scores categorized as low (1.5–3.0), moderate (3.5–5.0) and high (5.5–7.0) to (1) the source of the identified risk of the shafts, (2) the ways of exposure to the risk or pathways which the identified risk may affect the environment and (3) the potential impact (PI) of the risk to people, animals and other parts of the environment. The average score of the environmental as well as the safety and health risks of the shafts were used to compute their total hazard scores. The individual environmental risk ($E_{vr}$) scores of the shafts were calculated using Equation (1) which was developed for this research. In this equation, $Q_i$ was the source of the risk presented by the shaft, $P_j$ was the pathway (in the case of the problems of land degradation and impact on the aesthetic appearance of the environment; $P_j$ was assigned the value of 1) and $R_x$ was the magnitude of the consequences of the identified risk.

$$E_{vr} = Q_i \times P_j \times R_x$$ (1)
In order to calculate individual physical risk scores \( P_r \) of the shafts, Equation (2) was used. In this case, the value \( Q_s \), \( E_a \) and \( (N_i + M_i)/2 \) represent the source of the health and safety risks of the shafts, the way of exposure to the risks and the average of the magnitude of the shaft’s safety risks \( (N_i) \) and associated health risks \( (M_i) \). In cases where the shaft presented only safety or health risk, the absent factor was scored 0.

\[
P_r = Q_s \times E_a \times \left( \frac{N_i + M_i}{2} \right)
\]  

(2)

In order to determine the total hazard scores (i.e. environmental and physical hazard score), the averages of the scores of the respective individual risks were obtained and reduced to an easy to work with figures. The factor of 8 (NF) employed to reduce the magnitude of the scores was used for this purpose. This process can be mathematically expressed as shown in Equation (3):

\[
H_{Z_{\text{total}}} = \frac{\sum R_i \div NF}{n}
\]  

(3)

where \( H_{Z_{\text{total}}} \) is the total physical or environmental hazard, \( \sum R_i \) is the some of the scores of physical/environmental risks and \( n \) is the number of either physical or environmental risks identified.

The visual analysis of the structure of the scoring process represented by cobweb plots shown in Figure 2 demonstrated that in situations where the PI of the identified risks of the shaft is high (5.5–7.0 scores), the source of the risks (S) and exposure routes/pathways (E/P) are expected to take the scores ranging from 1.7 to 6.9 and 2.1 to 7.0, respectively. In the case where the PIs are moderate with 3.5–5.0 scores, the source and exposure to the risks of the shafts are to be assigned scores ranging between 2.0 and 6.7. Lastly, where the impact is low (1.5–6.2 scores), the source of the risks was expected to take scores ranging between 1.5 and 6.2 while the exposure routes/pathways are to have the scores of between 1.8 and 5.4.

2.3. Ranking of hazards
The hazard ranking criteria presented in Table 2 were developed based on the expected minimum and maximum total hazard scores of the scoring process. This hazard ranking criteria allowed that both physical and environmental hazards of abandoned shafts are classified into four categories.
(denoted as A, B, C and D). As depicted in Table 2, the system categorises the degree of the hazards into high (22–45), moderate (5–21), low (0–4) and negligible (<0). This classification of the hazards of the shafts allowed that their socio-economic concerns are classified in similar categories using the method described in Section 2.4.

### 2.4. Evaluation of socio-economic impact

Based on the expected range of total hazard scores and the ranking criteria presented in Section 2.3, the chart shown in Figure 3 was developed and used to quantify the socio-economic issues of abandoned shafts. The position of the mine shaft when its total environmental hazard score is plotted against its physical hazard score on the chart allowed that the socio-economic concerns of the shafts are classified as low, moderate and high. According to Figure 3, shafts with low socio-economic concerns fall in the zone of 0–4 zone on the chart while those with moderate and high fall between the zones of >4–21 and >21–45, respectively. The shafts with less than 0 physical and environmental hazard score were considered having socio-economic impacts that are at a negligible level.

The approach used to evaluate the socio-economic impacts of the shafts was developed based on assumption that physical hazards of abandoned shafts mainly affect the social well-being of the communities around the mine while the shaft’s environmental problems turn to affect the economic status of these communities. For example, open shafts near the communities are likely to present psychological and social challenges to the community while problems of ground instability and discharge of contaminated/acidic water turn to affect a larger part of the environment thus negatively affecting the economic value of the land.

### 3. Description of the case study

The Giyani and Musina areas are found in the Limpopo Province of South Africa as shown in Figure 4. These study areas are characterized by several abandoned underground gold and copper mining sites. The well-known abandoned copper mines in the area are Campbell,
Harper, Artonvilla, Spence and Musina mines while the gold mines include Klein Letaba, Louis Moore, Golden Osprey (also known as New Union), Fumani, Franke and Birthday mines. According to Wilson (1998) and Bahnemann (1986), large-scale underground copper mining was conducted around Musina between the years 1906 and 1991. Gold mining activities took place in the Giyani Greenstone Belt (GGB) from 1930 and ceased in the early 1990s (Steenkamp & Clark-Mostert, 2012). The exploitation of copper ceased when mining had gone beyond the depth of 1,310 m (Hammerbeck, 1976; Vesser, 1989). However, the gold mining operations in the GGB ceased when mining had just gone beyond 300 m.

The government and communities tried using different techniques to close-up some of the shafts with the purpose of reducing and/or eliminating their safety risks. However, a total of seven (18%) showed evidence of having never been closed. According to Chambers et al. (2007), the danger of shafts without lining or shaft collar is that their top part often turns to form a cone or creator with loose and unstable steeply dipping slopes. This makes it easier for people and animal to slide and fall into the deeper part of the shaft if they enter the upper cone part of the shaft. The strategies used to treat some of the mine shafts in the Giyani and Musina areas are heavy steel grate, concrete slab with steel wire screen, reinforced concrete slab, steel wire screens and concrete plugs as shown in Figure 5. The degree of use of these strategies in the study sites and their current conditions are depicted in Table 3.

Figure 4. The distribution of abandoned mine sites in the Giyani and Musina areas (Chaumba, Mundalamo, Ogola, Cox, & Fleisher, 2016; Parnham, n.d.).

Most shafts in these areas were once treated using steel grates and concrete slabs. However, these structures were vandalized or removed by illegal miners who enter the shafts to mine the remnants of gold deposits underground. To address this unfortunate setback in abandoned mine shafts treatment, concrete plugs which provide long-term treatment were used in closing a total of 13 shafts. The plugs were installed and buried at 3–10 m below the surface while only about 2.5 t concrete landmark is exposed on the surface (Department of Mineral Resources [DMR], 2010). In general, concrete plugs have an advantage of being self-supporting or anchored in the shaft while addressing risks of ground movement and falling into the shaft (Lecomte & Niharra, 2013).
4. Results
The inventory of abandoned shafts compiled through the review of literature about the studied abandoned mine sites and carry out the shaft’s preliminary field assessment allowed that their environmental and physical hazards are identified and quantified. The fact that the conditions and problems that prevail at abandoned mine sites vary from one site to the other makes the work of characterizing and prioritizing the rehabilitation of abandoned mines a real challenging undertaking (Fortier & Moore, n.d.). In view of this, the most common physical and environmental risks of abandoned mine shafts were used as the criteria for prioritization of their treatment. The physical risks considered in ranking the physical hazards were (1) physical injury due to falling into the mine shafts, (2) drowning in the water filling the underground mine workings, (3) exposure to dangers of rock/ground falls, (4) exposure to dangerous mine gases and (5) ingestion or getting to contact with contaminated mine water within the shafts. On the other hand, the environmental risks of the shafts that were considered were (1) the problems of land degradation that limits the alternative use of the land, (2) impacts of the abandoned mine shafts on the aesthetic beauty of the

Figure 5. The types of mine-shafts treatment options used in the study area. (a) Heavy steel grate, (b) concrete slab with steel wire screen, (c) concrete slab, (d) steel wire screen, (e) concrete plug and (f) is the shaft that was never closed.

Table 3. The efforts made in treatment of abandoned mine shafts in the Giyani and Musina areas

| State of the closing structure | Concrete slab | Concrete plug | Concrete slab and steel wire screen | Heavy steel grate | Never closed | Steel wire screen | Total |
|-------------------------------|---------------|---------------|-----------------------------------|------------------|--------------|------------------|-------|
| Never sealed                  | –             | –             | –                                 | –                | 7            | –                | 7     |
| Removed                       | 1             | –             | –                                 | –                | 2            | –                | 3     |
| Destroyed                     | 3             | –             | 2                                 | –                | –            | –                | 5     |
| Failed or failing             | 3             | 2             | –                                 | –                | –            | –                | 5     |
| Undamaged                     | 7             | 11            | –                                 | –                | –            | 1                | 19    |
| Total                         | 14            | 13            | 2                                 | 2                | 7            | 1                | 39    |
| %Total                        | 36            | 33            | 5                                 | 5                | 18           | 3                | 100   |

Note: – The issue not applicable.
landscape and (3) the potential contribution of the shafts to pollution of the environment. Based on the site investigation of the hazards of the shafts, numerical values were assigned to the source of the risk, way of exposure and PI to the victim. The values were assigned following the criteria presented in the methodology (Section 2.2) of this paper. Such numerical values were used to compute the scores that serve as measure of individual environmental or physical risk identified. The calculated scores for individual risks and the total environmental and physical hazards of the mine shafts are shown in Table 4. This approach of measuring the seriousness of the hazards of abandoned mines is comparable to that developed by Mhlongo et al. (2013) by modifying the HMS-SS used to rank historic mine sites in Ireland.

4.1. The risks of abandoned mine shafts

The scoring of hazards of the shafts showed that mine shafts in the Giyani and Musina areas had physical hazards that are slightly higher than environmental concerns. A large group of shafts that had relatively high physical hazard scores were in the Musina area. These shafts had increased risks of falling into them since they were found open or inadequately closed and in highly unstable/subsiding grounds. Such ground instability also resulted to these shafts having higher risks of rock falls which present safety threats to adventurous people who might want to enter the underground mine workings. Moreover, the greater depth of mining (>1,300 m) in the Musina area contributed to the risk of falling into the shafts being rated high. This is because this risk of old shafts is likely to result to death with no hope for successful recovery of the body.

Comparatively, the shafts that were never treated or those which the structure used to treat the shafts was vandalized by illegal miners in the Giyani area were found with relatively low risks of falling into the shafts and rock falls (see Figure 6a). The fact that these shafts were without lining structures and/or shaft collars increased the risks of falling into them. Moreover, the fact that illegal miners operations at the GGB (especially at Klein Letaba Mine) go underground through the old inclined shafts in their endeavours of exploiting the remnants of the deposit underground made the exposure to the risks of drowning in water filling the mine workings, accidental or voluntary ingestion of contaminated mine water in the underground environment and getting exposed to harmful mine gases slightly higher than in the case of the copper mine shafts (see Figure 6a).

In general, the major environmental problems of abandoned mine shafts or entries are that they are at times found discharging contaminated and acidic water. The shaft that is used to pump water for irrigation and other domestic purposes at Klein Letaba Mine was the only shaft that had relatively higher pollution potential risk score in the whole of the study area. However, the major environmental issues of most of the shafts in the Giyani and Musina areas were physical degradation of the land which also affects the aesthetic appearance of the landscape. The shafts found in physically unstable grounds in Musina had the highest score for land degradation issues (see Figure 6b). The reason for this was that the land occupied by these shafts is at the state where it cannot support even the basic post-mining land uses such as crop farming and development of animal grazing site. The comparison of the seriousness of the risks of abandoned shafts which gives an indication of what should be the focus of the efforts of treatment of the shafts in the areas of Giyani and Musina is shown in Figure 6a and b.

4.2. Physical and environmental hazards of the shafts

Although the government tried addressing some of the safety risks of the mine shafts in the Giyani and Musina area, these shafts were found still presenting varying degrees of physical and environmental hazards. The total physical hazard scores of the shafts ranged between 1.2 and 26.8 while the environmental hazards ranged between 7.2 and 21.6. The main reason behind these distributions of the total hazard scores can be as a result that the shafts which were treated with temporal structures with the purpose of reducing or eliminating their safety risks had a comparatively higher environmental hazard (most relating to subsiding grounds around the shafts). For example, a total of 21 shafts (i.e. 54% of the total) which were well treated with concrete plugs
| No. | Shaft-ID | Latitude | Longitude | Physical risks | Environmental risks | Total physical hazard score | Aesthetic appearance | Total environmental hazard score | Land degradation | Pollution potential | Total physical hazard score | Aesthetic appearance | Total environmental hazard score |
|-----|----------|----------|-----------|---------------|-------------------|-------------------------|----------------------|-----------------------------|----------------|------------------|------------------------|----------------------|-------------------------|
| 1   | MCM-1    | 22° 20' 15" | 30° 02' 30" | 1.69   | 1.1   | 0.5   | 1.0 | 1.7 | 0.15 | 12.0 | 3.4 | 2.3 |
| 2   | ATV-1    | 22° 18' 14" | 30° 05' 45" | 15.5  | 3.8   | 2.5   | 5.0 | 3.6 | 0.76 | 18.0 | 3.4 | 2.3 |
| 3   | ATV-2    | 22° 18' 33" | 30° 05' 38" | 119.3 | 17.7  | 0.5   | 11.3 | 11.1 | 4.35 | 20.0 | 3.4 | 9.0 |
| 4   | ATV-2    | 22° 22' 29" | 30° 09' 14" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 3.34 | 20.0 | 3.4 | 9.0 |
| 5   | ATV-2    | 22° 22' 31" | 30° 09' 30" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 4.35 | 20.0 | 3.4 | 9.0 |
| 6   | ATV-2    | 22° 22' 14" | 30° 09' 54" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
| 7   | ATV-2    | 22° 22' 33" | 30° 09' 38" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 10.5 | 20.0 | 3.4 | 9.0 |
| 8   | ATV-2    | 22° 22' 29" | 30° 09' 14" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 4.35 | 20.0 | 3.4 | 9.0 |
| 9   | ATV-2    | 22° 22' 31" | 30° 09' 30" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
| 10  | ATV-2    | 22° 22' 31" | 30° 09' 32" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
| 11  | ATV-2    | 22° 22' 31" | 30° 09' 34" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
| 12  | ATV-2    | 22° 22' 31" | 30° 09' 36" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
| 13  | ATV-2    | 22° 22' 31" | 30° 09' 38" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
| 14  | ATV-2    | 22° 22' 31" | 30° 09' 40" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
| 15  | ATV-2    | 22° 22' 31" | 30° 09' 42" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
| 16  | ATV-2    | 22° 22' 31" | 30° 09' 44" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
| 17  | ATV-2    | 22° 22' 31" | 30° 09' 46" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
| 18  | ATV-2    | 22° 22' 31" | 30° 09' 48" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
| 19  | ATV-2    | 22° 22' 31" | 30° 09' 50" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
| 20  | ATV-2    | 22° 22' 31" | 30° 09' 52" | 171.5 | 6.0   | 0.5   | 11.3 | 9.08 | 6.75 | 20.0 | 3.4 | 9.0 |
### Table 4. (Continued)

| No | Shaft-ID | Latitude | Longitude | Coordinates | Physical risk | Environmental risk |
|----|----------|----------|-----------|-------------|---------------|--------------------|
|    |          |          |           |             | Physical body injury | Drowning hazards | Intake of contaminated water | Mine gases | Rock falls | Total physical hazard score | Land degradation | Pollution potential | Aesthetic appearance | Total environmental hazard score |
| 24 | BDM-5    | 23° 19′ 29″ | 30° 46′ 14″ | – | – | – | 1.7 | – | 0.04 | 4.0 | 4.5 | 4.0 | 0.52 |
| 25 | BDM-6    | 23° 19′ 28″ | 30° 46′ 14″ | – | – | – | 1.7 | – | 0.04 | 4.0 | 4.5 | 4.0 | 0.52 |
| 26 | BDM-7    | 23° 19′ 38″ | 30° 46′ 16″ | – | – | – | 1.7 | – | 0.04 | 4.0 | 4.5 | 4.0 | 0.52 |
| 27 | BDM-8    | 23° 19′ 39″ | 30° 46′ 16″ | – | – | – | 1.7 | – | 0.04 | 4.0 | 4.5 | 4.0 | 0.52 |
| 28 | BDM-9    | 23° 19′ 38″ | 30° 46′ 18″ | – | – | – | 1.7 | – | 0.04 | 4.0 | 4.5 | 4.0 | 0.52 |
| 29 | BDM-10   | 23° 19′ 35″ | 30° 46′ 15″ | – | – | – | 1.7 | – | 0.04 | 4.0 | 4.5 | 4.0 | 0.52 |
| 30 | NUM-1    | 23° 01′ 23″ | 30° 43′ 37″ | 105.6 | 8.3 | – | 4.0 | 50.0 | 4.20 | 36.0 | 18.0 | 36.0 | 3.75 |
| 31 | NUM-2    | 23° 01′ 28″ | 30° 43′ 31″ | 105.0 | 22.0 | – | 13.5 | 37.5 | 4.45 | 25.0 | 3.4 | 25.0 | 2.22 |
| 32 | NUM-3    | 23° 01′ 11″ | 30° 44′ 6″ | 171.5 | 7.0 | 1.7 | 7.8 | 4.0 | 4.80 | 36.0 | 3.4 | 36.0 | 3.14 |
| 33 | NUM-4    | 23° 01′ 08″ | 30° 44′ 08″ | 147.0 | 9.0 | – | 4.0 | 60.0 | 6.59 | 36.0 | 3.4 | 49.0 | 3.68 |
| 34 | NUM-5    | 23° 01′ 28″ | 30° 43′ 31″ | 171.5 | 20.3 | – | 4.0 | 60.0 | 6.99 | 36.0 | 3.4 | 49.0 | 3.68 |
| 35 | NUM-6    | 23° 01′ 21″ | 30° 44′ 2″ | 171.5 | 7.0 | – | 4.0 | 24.0 | 5.16 | 42.0 | 3.4 | 49.0 | 3.93 |
| 36 | NUM-7    | 23° 01′ 21″ | 30° 44′ 3″ | 171.5 | 7.0 | – | 4.0 | 24.0 | 5.50 | 33.0 | 3.4 | 33.0 | 2.89 |
| 37 | LMM-1    | 23° 13′ 13″ | 30° 41′ 68″ | 171.5 | 78.0 | – | 4.0 | 108.0 | 9.04 | 30.0 | 4.80 | 32.5 | 4.60 |
| 38 | LMM-2    | 23° 13′ 13″ | 30° 41′ 45″ | 171.5 | 153.0 | – | 4.0 | 75.0 | 10.09 | 30.0 | 4.80 | 36.0 | 4.75 |
| 39 | LMM-3    | 23° 13′ 13″ | 30° 41′ 66″ | 56.0 | 3.4 | – | 4.0 | 1.7 | 1.63 | 25.0 | 4.80 | 25.0 | 4.08 |
and slabs had low physical hazard score of 3.4 while the four shafts (10% of all studied shafts) which had collapsed treatment structures in highly physically unstable ground had the highest physical hazards score of 26.8.

Based on the hazard classification scheme developed and used in this work, about 10% of the shafts had physical and environmental hazard scores of 26.8 and 21.6 scores, respectively. These shafts were therefore found to be in to Category-A (high hazard class) in the hazard ranking. Many shafts (60% of the shafts) had moderate physical hazards while 16% of the shafts were placed in Category-C with low physical hazards. However, most of the shafts which were never closed or those which their treatment structures were vandalized had a physical hazard score that place them on the breaking point value between moderate and high physical hazards as shown in Figure 7. It was also found that a very high percentage (90%) of all studied mine shafts had moderate environmental hazard scores and were thus classified under Category-B.
4.3. Socio-economic issues of the mine shafts

Plotting the environmental and physical hazard scores on the developed socio-economic impact evaluation chart showed that the shafts in the Giyani–Musina areas are generally characterized by low-to-moderate socio-economic concerns. According to Figure 6, the shafts found with intact treatment structures (i.e. concrete plugs and slabs) had negligible and very low socio-economic issues. The untreated shafts, those for which treatment structures were vandalized or removed, and the only shaft used to pump ground water for irrigation and domestic uses were classified as having moderate social problems than economic concerns (see Figure 8). The uses of abandoned gold mine shafts for illegal/artisanal gold mining activities were identified as the major social concerns of these shafts. This is because these activities expose many people to different health and safety risks of the abandoned shafts. These activities are also associated with several environmental problems such as cutting and/or uprooting of trees and deposition of contaminated soils from the abandoned mine sites into nearby rivers during the process of sluicing to concentrate gold from material extracted underground and around the mine (Magodi, 2017). On the other hand, the major social concern of the abandoned copper mining shafts is that these shafts are used as storage...
sites for illegal or stolen items. The other use of the shafts observed in the Giyani area was dumping of water that is used for domestic purposes through the abandoned shafts.

5. Discussion

This work showed that although the existence of abandoned mines in the Giyani and Musina areas is known, there is still a need for systematic mapping and characterization of individual features of these mines. The importance of such an initiative is that hidden features such as mine shafts can be located, their hazards identified and evaluated and the objectives of their treatments defined. This can reduce the prevalence of situations were some of the features get to be left out in the rehabilitation process and were the use of inappropriate rehabilitation strategies (as it happened with the treatment of abandoned mine shafts in the Giyani and Musina) areas is avoided.

According to Matshusa and Makgae (2014) and DMR (2010), the presence of open shafts on the abandoned mine lands of Giyani and Musina areas was the reason these mines were classified as high-priority mines in the national abandoned mines rehabilitation programme. In view of this, the work of treating abandoned shafts or mine entries in these areas has been ongoing for many years. Even though this is the case, a total of seven shafts at New Union Mine (GGB) appeared to have been omitted in work of treatment of the shafts while some were treated with strategies that barely addressed the major problems of these shafts.

The ranking of the hazards of abandoned mine shafts showed that falling into the shafts and the problems of ground movements around the shafts were primarily their physical and environmental risks. The predominance of these risks was promoted by the fact that these shafts were found adjacent to densely populated communities. Moreover, some of them were in unstable or subsiding grounds while others were used by illegal miners to go underground in their mining endeavour. This suggests that treatment strategies with a potential of providing long-term sealing of abandoned shafts while preventing the problems associated with the movement of the ground around the shaft should be considered first in the treatment of abandoned mine shafts to address their physical and environmental hazards. The treatment strategies for effectively addressing the problems of abandoned mine shafts in the study area are presented in Table 5. These shafts treatment strategies also have high potential of minimising or eliminating the problems of ground fall, release of toxic gases and discharge of contaminated water.

It is important to note that the success of most abandoned mine rehabilitation efforts also depends largely on prevailing socio-economic issues in the communities around the mines. For example, mine shafts treated with credible sealing structures such as concrete slabs and steel grate were in few months completely vandalized by illegal mines in the Giyani and Musina areas. Contrary, in Oklahoma (USA), the mine shafts closed using old car bodies and railroad ties lasted for 60 years without a need for replacement or maintenance (Graves et al., 2000). Based on the

| Shaft treatment strategies | The risks being addressed by the treatment strategies |
|----------------------------|-----------------------------------------------------|
|                            | Physical injury | Ground movement | Gas emission |
| Backfill                   | ✪              | ✪               | ×            |
| Self-supporting plug       | ✪              | ✪               | ☆            |
| Anchored plug              | ✪              | ✪               | ☆            |
| Surface cap                | ✪              | ✪               | ×            |
| Blast closure              | ✪              | ✪               | ×            |
| Injection                  | ☆              | ✪               | ☆            |
| Geo-synthetics             | ☆              | ☆               | —            |

Source: Lecomte and Niharra (2013).

Note: ✪ Most suitable technique for the risk, ☆ with modification; the technique can address the risk, × poorly performing technique in addressing the risk, and — not suitable for the risk.
socio-economic evaluation of abandoned mine shafts conducted in this work, it was only the shafts closed with concrete plugs that were found with negligible level of socio-economic concerns. One of the reasons for these is the fact that this shaft treatment strategy can provide long-term treatment of the shaft. According to Graves et al. (2000), concrete plugs can effectively close old mine shafts for a period of not less than 100 years.

The method developed for ranking of hazards of abandoned mine shafts in this work is generally consistent with the generic rational decision-making processes as explained by Turpin and Marais (2004). Such an approach involves finding occasions of deciding through conducting a preliminary field assessment of the mine shafts, investigating and/or analysing the possible sources of action through identification of the sources of physical and environmental risks of the shafts and selecting a source of action by ranking the risks presented by the shafts. This method has the advantages of being methodological which make it easy to understand and apply in different situations of abandoned mine shafts. It is also less data demanding when compared with other popular strategies used to prioritize rehabilitation options of abandoned mines. However, although the hazards scoring process is criteria guided, assigning of actual scores to represent the seriousness of the component of the risk identified is based on the judgement of the experts assigning the scores. In view of this, the method is best suited for preliminary assessment and prioritization of hazards of abandoned mine shafts.

The ranking of abandoned mine shafts based on information gathered during preliminary field assessment of the shafts is comparable with that used by the risk ranking methodology employed in ranking abandoned mines in the British Columbia in 2007/8 (Power et al., 2009). The development and use of abandoned mines ranking systems that use basic information gathered from preliminary field assessment of the mine features are the sound bases for effective mine site rehabilitation for developing countries with large number of abandoned mine sites like South Africa and with limited resources to rehabilitate the numerous sites. This approach requires that detailed characterization of these sites be done after conducting preliminary site characterization.

6. Conclusion

In general, abandoned mines with dangerous shafts in the Giyani and Musina areas are situated near communities; thus, it is important that their treatment is considered urgent and be done in a more effective manner. The treatment of these shafts will significantly improve the safety status of the abandoned mine sites and make the land they occupy available for other traditional post-mining land uses. Such productive use of abandoned mine lands will go a long way in addressing some of the socio-economic issues that prevails in communities around these mines.

The hazard ranking system developed and used in this work has proven to be robust and reliable in providing information required to make sound decisions in the treatment of abandoned mine entries. The results provided by the system also provide guidance on the type of treatment strategies to be considered in dealing with physical hazard and environmental problems of abandoned mine entries while addressing their socio-economic concerns. Its application in the situation of abandoned mine shafts in the Giyani and Musina areas revealed that the shafts in these areas have moderate physical and environmental hazards and corresponding socio-economic concerns. Risks of falling into the shafts and problems of ground movement which degrade the land around the shafts were found to be the dominant physical hazards and environmental problems of the shafts.

The fact that the system developed provides ranking of the hazards based on information collected by conducting preliminary field assessment of the mine entries, it was therefore found appropriate for use in developing countries where there are numerous abandoned mines and limited resources to rehabilitate them. This will go a long way in ensuring that characterization and rehabilitation of the abandoned mine entries are effectively carried out with limited resources.
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