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A review of problems and solutions of abandoned mines in South Africa

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Mining has been the backbone of the South African economy for many years. For over a century it has contributed considerably in the welfare of the people of South Africa. As a result of South Africa's long history of mining, the country has many abandoned mines that are currently the major source of various environmental and social problems. This review looks at the general problems of abandoned mines in South Africa and the efforts made towards rehabilitation of abandoned mine sites. The issues discussed include the controversy around the definition of abandoned mines, their associated problems, regulatory issues, prioritisation of rehabilitation and the rehabilitation cost estimation concerns. It was concluded that in order to fast track the work of cleaning up the negative legacy of abandoned mines in South Africa, appropriate definition for these mines should be identified and used in guiding the work of developing the country's abandoned mines inventory while assisting in the prioritisation of rehabilitation efforts. The abandoned mines rating system and the cost estimation model that can account for the site-specific issues in the rehabilitation of abandoned mines were recommended.

Keywords: abandoned mines; mine rehabilitation; public safety; South Africa

1. Abandoned mines issues

Most common abandoned mine issues in countries with long histories of mining like South Africa include environmental stresses, public health and safety concerns, and socio-economic impacts [1,2]. These mines are considered by many as negative legacy of post-mining operations. Although the problems of derelict mining sites are well known in almost all countries, the efforts of the mining industry, governments and the host communities towards their rehabilitation have not been very encouraging. According to UNEP and COCHILCO [3], the reasons for the delay in rehabilitation of abandoned mines are lack of clearly assigned responsibilities, the absence of criteria and standards of rehabilitation for these mines, and the potential high cost of rehabilitation. The main reason for the delay is that abandoned mine rehabilitation projects are invariably expensive and often have no clear view of where the necessary funds will come from as the economic phase of the mine will have ceased [4].

Abandoned mines (especially abandoned gold mines) turn to be hot spots for small-scale and illegal mining operations which are practices that promote both environmental and physical hazard problems. The abandoned mines together with illegal small-scale

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mining operations were reported by Steenkamp and Clark-Mostert [5] to be affecting the water courses in the vicinity of Giyani area of South Africa. In this region, artisanal illegal miners dig out washing sites, dam water and build sluice tables along the river banks. In addition, in most instances, small-scale miners dig their own access ways into the old underground workings and manually extract ore from underground [5]. These have increased the community exposure to physical and health hazards of abandoned mines in the areas. According to Reichardt [6], artisanal small-scale operations around the abandoned or historic mines can be considered to be threats to the viability of mine closure and rehabilitation efforts. Incidents that occurred in 2006 and 2007, where 5 and 61 illegal miners died due to rock fall and mine fire in inactive shafts of Fairview Mine in Barberton and Harmony Gold Mine in the Witwatersrand, respectively, are indications of human tragedy that can result from illegal mining operations in abandoned or inactive mine sites [6,7].

2. Definition of abandoned mines

On the whole, there is no clear and widely accepted definition of abandoned mines. The mine is generally considered abandoned if there are no identified owners or operators for the facilities. The term can also be used to describe sites where the proponent has ceased or suspended operations until further notice [8]. Section 46 of the Mineral and Petroleum Resources Development Act (MPRDA) (Act No. 28 of 2002) of South Africa classifies those mines for which a closure certificate has not been issued and no party can be traced to assume responsibility for their liabilities as abandoned and the government may provide funds for their rehabilitation. The other terms used to refer to these mines include derelict mines, orphan mines, unattended mines and inactive mines. According to Mackasey [9], in the selection of an appropriate definition of abandoned mines, the consideration of public safety and health together with environmental hazards associated with these mines are of great significance than the ownership aspects.

According to Newton et al. [10], abandoned mines can be defined as any mineral extraction, exploration or borrowed operation where operations have ceased for a period of one year or more, where there is no interim management plan in effect, and where there are no approved financial assurances that are adequate to perform reclamation. These sites include but are not limited to shafts and adits, buildings and workings, open pits, stockpiles, roads, mineral processing areas and facilities, and waste disposal areas such as tailing dumps and ponds. As a result, abandoned mine sites can be precisely defined as mine sites and mineral operations that are no longer operational, not actively managed, not rehabilitated, causing significant environmental and/or social problems, and for which no one is currently accountable for the site's remediation or rehabilitation.

3. Environmental problems of abandoned mines

Generally, the major factors contributing to the environmental problems of mining are the type of mining method employed in the extraction of mineral resources and the geographical location of the mine [11]. This is basically due to the fact that the nature of land disturbances that are associated with surface mines is usually different to those that are found in underground mining operations. According to Allen et al. [12], the type of mining method affects the visual appearance of the area, which is generally the mining lease area. However, a relatively large area outside the mine lease area is mostly affected by pollution and accumulation of waste material from the mine [12,13]. Currently, the environmental problems associated with mining operations are minimised through the use of well-designed, well-operated and well-regulated mining operations. However, in all mining countries and/or regions there are many abandoned mines that remain a major source of environmental problems.

The common physical and environmental problems characterising most abandoned mine sites include altered landscape, unused pits and shafts, land no longer usable due to loss of soil, harsh pH levels, areas of steep slopes, abandoned mine waste disposal facilities, changes in ground and surface water regimes, contaminated soils and aquatic sediments, subsidence, changes in vegetation cover, derelict sites with compacted soil and burning coal waste dumps and workings [14]. Water resources which are also conduits through which contaminants escape to the environs away from the immediate mine sites are most frequently polluted by abandoned mines. The chemistry of the discharge by mines varies greatly and their effect differs, thus the drainage from the mines may be alkaline, moderately or highly saline, alkaline and ferruginous or acidic and ferruginous [15]. The major problem affecting water resources throughout the world is acid mine drainage (AMD). In South Africa, acid mine drainage problems worsen daily. According to Makgae [16], the AMD issue has for the recent past received considerable attention and has become a costly environmental challenge facing the South African Government. This is generally a process that occurs as a result of the interaction of oxygenated water with sulphides, especially pyrite (FeS_2) minerals [17,18]. According to Nordstrom and Alpers [19], from an acid-generation perspective, pyrite is the most relevant sulphide due to its grain size and distribution.

It is not all South African mineral deposits that are associated with the production of AMD; the country's extensive coal and gold fields (Witwatersrand basin) characterised by high number of abandoned mine sites contribute significantly in the discharge of acidic water into the major rivers of South Africa [17]. The acid mine drainage potential areas in South Africa are shown in Figure 1. The AMD problem in the country is likely to persist for centuries to come [20]. This is due to the fact that within the Witwatersrand area alone, there are huge pyrite-bearing tailings (6 billion tonnes over 400 km^2) that are expected to continue releasing acidic water that leaches iron and sulphides to the environment [21–23]. In addition, despite the fact that AMD from abandoned coal mines is already affecting water quality in the Olifants River Catchment, prospecting rights across 45% of Mpumalanga land mass are still being granted, thus giving clear indications of the future potential of AMD generation in the country [24].

4. Socio-economic impacts of abandoned mines

Mining by its nature brings to the communities enormous investment, thus contributing to the socio-economic development of the host communities. Some of the socio-economic benefits of mining include the development of new job opportunities in the area, infrastructural development and attraction of basic needs such as running water, electricity, building of schools and health care centres. The socio-economic opportunities that are presented by mining ventures are the reason for the mushrooming of new communities around the mine sites. Where these communities exist, they remain the issue of concerns due to the fact that they become absolutely dependent on the economic opportunities generated by the mine. As a result, abandoned mines are commonly found within communities of which some are densely populated. Figure 2 shows the

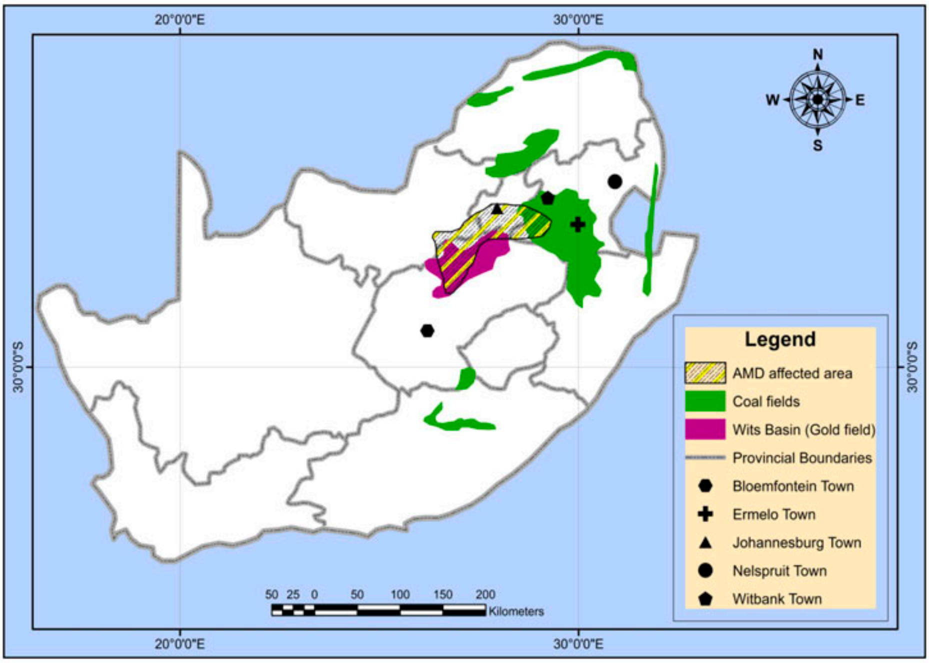

Figure 1. Potential areas of acid mine drainage in South Africa (modified from report to the inter-ministerial committee of Acid Mine Drainage, 2010).

relative position of abandoned mines within densely populated communities in South Africa.

Frequently, the environmental stresses of abandoned mines can as well have severe impact on the quality of life and livelihood of people around the abandoned and/or historic mines. According to Johnston et al. [15], iron-rich water from the mines might have an aesthetic impact on the receiving water bodies, thus making the place less attractive for investment. This also makes the water unsuitable for other uses and as a result reduces the economic and social value of the water to the surrounding community.

The water with high content of uranium (900–1000 ppm) and other contaminates or heavy metals such as cobalt (Co), zinc (Zn), arsenic (As) and cadmium (Ca) from the abandoned gold tailings at Wonderfonteinspruit Catchment (West and Far West Rand) was reported to be posing serious health hazards to the communities around the area. These problems are exacerbated by the fact that most of the inhabitants of this area live in informal settlements with high HIV/AIDS infections, chronic and acute malnutrition and as a result, the detected uranium level poses additional stress to their immune systems [25]. The major socio-economic problems of abandoned mines include a decrease in the number of residents and visitors to previous mining areas, financial impact on communities and creation of 'ghost towns', increased social and community resistance to mining, loss of jobs and livelihoods, loss of sense of community, loss of services, loss of opportunities for local people and impact on local councils and their ability to sustain the infrastructure brought by the mine [26]. According to MMSD [14], the death of fish as a result of the dispersion of pollutants to surface water bodies has a potential of affecting the livelihood of communities that depend on fishing.

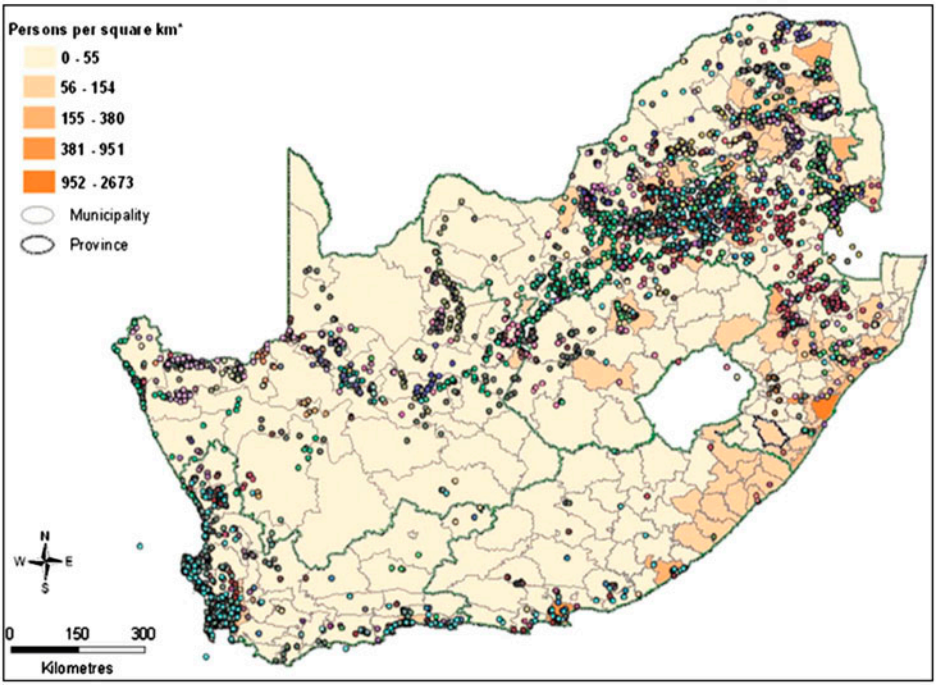

Figure 2. Abandoned mines within the vicinity of South African settlement areas (from Auditor General South Africa, 2009).

Other socio-economic issues that arise from the environmental problems of inactive or poorly rehabilitated mines are loss of productive land, degradation of water resources which in turn have detrimental effects to aquatic life, change in river regimes, air pollution from dust and toxic gases, risk of injury or death as a result of falling into open shafts and pits, and risks of landslides [3]. In addition, dust and soils from abandoned mines might contain contaminants (silica, asbestos fibres, chromium and heavy metals) that are hazardous to health.

5. Legislative framework and rehabilitation prioritisation

South Africa's economy has heavily relied on mining activities for over a century and continues to do so. Unfortunately mining has also left the country with enormous economic, social and environmental problems [27]. Mining in South Africa operated for a long time under traditionally weak regulation systems that placed the responsibilities for mining impacts to the mine owners and in the process many mines (i.e. approximately 6000 mines) were abandoned [28]. In the past, mining companies could abandon mines and leave the liability of mine closure and rehabilitation to governments and communities [1]. According to Swart [27], prior to the endorsement of the Minerals Act (Act 50 of 1991), many mining companies used irresponsible mining methods with no regard towards protecting the environment and left these mines unrehabilitated prior to them being liquidated or leaving the country. The Minerals Act (Act 50 of 1991) was passed with the objectives of ensuring that the responsibilities of the state towards the community in respect of the mineral industry are fulfilled. These responsibilities include the regulation of prospecting for minerals and optimal exploitation; processing and utilisation of minerals; and the orderly utilisation and rehabilitation of the land where prospecting and mining operation have or are taking place [29].

The previous (apartheid) government attempted to deal with the abandoned mines situation in South Africa through the 1975 Fanie Botha Accord agreement between the Minister of Water Affairs and the Chamber of Mines [28]. On this, it was agreed that the government would assume 100% responsibility for all mines which were closed before 1976 and 50% responsibility for those that closed between 1976 and 1986 rehabilitation, while the other 50% is taken care of by the mine owner. It was also agreed that after 1986 rehabilitation of all mines including their closure were to be the responsibility of the owner [14,28].

Currently, the abandoned mines in South Africa are regulated under the mineral regulation branch of the Mineral and Petroleum Resources Development Act 2002 (MPRDA). The main functions of the mineral regulation subdivision are to:

- Administer the MPRDA 2002,
- Promote mineral development including urban removal, rural development and black economic empowerment,
- Address past legacies with regarding to mine rehabilitation by means of regulated environmental management plans and
- Coordinate and liaise with national, provisional and local government structures for efficient government. The other branches of the MPRDA 2002 are mineral promotion and policy formation subdivisions.

Although the most important and well-documented issues of abandoned mines are physical hazards, environmental problems and socio-economic issues [1,2], the major focus of abandoned mines rehabilitation agenda in South Africa has been on those mines that present significant amounts of health and safety hazards. According to the official statement from Department of Mineral Resources (DMR), the rehabilitation of abandoned mines in South Africa since 1986 has focused on health hazardous asbestos mines and public safety threatening mine shafts [30,31]. In response to the 2006 Auditor-General South Africa report and the outbreak of AMD-related problems in the Witwatersrand, the DMR (the former Department of Minerals and Energy) grouped those mines that pose high environmental risks at high priority following the heath hazardous abandoned mines as shown in Table 1.

6. Rehabilitation of historic mines

There are several issues that need to be taken into consideration when assessing an abandoned or inactive mine site for rehabilitation purposes. These issues include the age of the mine site, the level of environmental impact presented by the site, public safety and health issues, social issues, availability of government support and the commitment of the community to rehabilitation effort. According to Goldammer and Nüsser [32], the rehabilitation of contaminated mines requires appropriate and efficient decision-making methodologies, thus the goals of rehabilitation are to protect the people and the environment while saving money and other resources. In this regard, the rehabilitation of abandoned mine lands is not an exception. In South Africa and other countries, first priority in the rehabilitation of abandoned mines is given to those mines that present severe public safety concerns and then to those characterised by adverse impact

Table 1. High priority abandoned and historic mines in South Africa.

Region	Commodities	Comments
Asbestos mines	Asbestos	High risks due to adverse health impacts
Wits gold basin (from the Free State to Evander)	Gold and uranium	High environmental risks due to uranium content and acid mine drainage (AMD)
Gold mines occurring in the greenstone belt of Mpumalanga	Gold, silver and arsenic	High risks due to arsenic, AMD and uranium content
Gold occurring in the greenstone belt in Limpopo	Gold and antimony	High risks due to AMD and the presence of antimony and, in some cases, mercury
Coal mines in Mpumalanga	Coal	High risk due to land subsidence, AMD and spontaneous combustion
Copper mines	Copper, tungsten, molybdenum and bismuth	Water-related risks due to the presence of bismuth – medium risk
Pegmatites in Northern Namaqualand	Many commodities	Risks are primarily due to radioactive components or bismuth – medium risk

Source: Ref. [41].

to the environment [14,30,31]. In view of this, in all phases of rehabilitation of abandoned mines, there is very little attention that is given to the socio-economic issues of these mines. According to Mitchel and Mackasey [33], the only rating system that takes environmental, public safety, public health and socio-economic impacts of abandoned mines into consideration is that jointly developed by MNDM and Laurentian University. The system was developed for the purpose of prioritisation of over 6000 abandoned mines in the Province of Ontario.

Over the years, there has been a noticeable shift in the strategies used to rehabilitate mined land. In South Africa within the past 40 years, mine rehabilitation has moved through three phases, that is from land stabilisation to monotonous grasslands and to a multiplicity of different landscapes/habitats or ecotopes [34]. Some of the most common mine rehabilitation approaches that are also used in reclamation or remediation of abandoned mines are shown in Table 1 of Appendix 1. In cases where rehabilitation of historic mines is found necessary, it should be based on intensive research-based studies that evaluate the reactivity of the minerals in question with the fluids that they are now in contact with, and the likely reaction products [35].

7. Abandoned mines rehabilitation cost estimation

There are basically two popular models used to estimate mine closure and rehabilitation cost and those are Mine Closure Model (MCM) and Rule-Based Model. According to du Plessis and Brent [36], the MCM describes the way the mine closure or rehabilitation can be carried out in a more systematic manner based on project management principles, while the Rule-Based Model is the closure costing approach that describes the methodology for determination of the quantum for financial provision, and thus the model is currently used by DMR. In addition to these methods, mine closure costs can also be estimated through the use of decision tree developed from closure elements and Monte Carlo simulation (also known as probability simulation) [37]. The minimum requirements for acceptable cost estimation methods are that it includes a quantified detail of rehabilitation work and that should include costs against each line item, subtotals and total costs as well as the schedule of unit costs. On this, the basic costs for mine rehabilitation are mobilisation costs; project management cost (which is 10% of the total), monitoring costs (made up of 5% of the total), contingency costs (made up of 10% of the total) and the indexation for inflation [38]. In addition, it is generally easier to estimate the minimum and maximum costs for a mine closure project than to determine a specific figure or cost [37]. According to van Zyl et al. [39], the mine closure cost should be estimated based on the selected appropriate closure technology and also according to the cost of implementation of the selected strategy as well as the socio-economic closure measures.

The rehabilitation of abandoned mines is generally a costly project, especially because it is normally not clear on who should provide funds for this undertaking. In many countries including South Africa, the costs of cleaning up the negative legacy of abandoned mines are borne by the government. In addition to the stated challenges with regard to funding of abandoned mines rehabilitation projects is the fact that the costs of carrying out this work are mostly uncertain. The reason for this is mainly that the costs for rehabilitation of abandoned mines depend exceptionally on the rehabilitation strategies adopted and the standards it is pursued. Moreover, these costs are also affected by the lack of agreed criteria as to what conditions need to be remediated and what should be the goals for rehabilitation [14]. The uncertainty with regard to the number and state of abandoned mines also makes it impossible to estimate their rehabilitation costs with the necessary precision. The nature of rehabilitation work was mentioned by van Zyl et al. [40] as one of the factors that makes the determination of abandoned mines rehabilitation costs complex. The estimated cost for remediation of current officially listed abandoned mines in South Africa is R30 billion, which is just a contingent figure that was estimated based on the cost incurred on the rehabilitation of asbestos mines projects during 2007 and 2008 period [31,40].

8. Discussion

Our analysis of abandoned mines situation in South Africa revealed that although a lot is being done in compiling the abandoned mines inventory and addressing their associated hazards, much is still required. To start with, the issue of definition of abandoned mine needs to be addressed. This is due to the fact that South Africa has a number of historic mines for which the owners can be traced but without funds to carry out the rehabilitation work. These mines continue to be a major source of enormous level of environmental hazards, physical hazards and socio-economic impacts. Consequently, although the ownership is important in the classification of historic mines as abandoned or inactive, the seriousness of hazards they present and the type of features that constitute historic mine site are of great significance and are to be considered in the definition. An appropriate definition will go a long way in eliminating duplicates in the country's abandoned mines data-base, as it will assist in identifying the abandoned mine sites as well as the various features constituting the site. For example, this is due to the fact that currently if one mining site is having three shafts, the site is subsequently recognised as three abandoned mines. In addition, it will allow that historic mine sites are considered abandoned after having characterised in terms of their ownership status, associated hazards and socio-economic concerns. This will have benefits of easy rating of these mines in order to prioritise their rehabilitation.

Although it is a known fact that abandoned mine sites are associated with high levels of environmental problems, physical hazards and socio-economic issues, the abandoned mines rehabilitation programme in South Africa appears to be more focused on addressing the public health and safety threats presented by these mines, while environmental problems are second in priority. There has been no/less an effort made in addressing the socio-economic impact of abandoned mines in the country. In order to easily tackle this problem, it is necessary that appropriate criteria or strategies for ranking abandoned mine sites are developed. In this regard, the ranking approach should take into consideration the site-specific nature of environmental and physical hazards as well as the socio-economic impacts of the abandoned mines.

The problems of abandoned mines in South Africa vary from one site to the other: according to the type of commodity mined and the type of mining and mineral processing methods used. The knowledge of the problems of abandoned/historic mines gathered during site characterization and rating stages can form a solid basis on which sound decisions with regard to the selection of the most appropriate (i.e. site specific), and less costly rehabilitation options can be made. In this, the most appropriate rehabilitation strategies for abandoned mines should address both environmental and physical hazard problems, while improving social and economic status of the host community. As a result of the fact that the applicability and success of abandoned mines rehabilitation strategies depend mostly on site-specific issues, the method of estimating the cost of abandoned mines rehabilitation work should take into consideration the site-specific issues. A summary of the procedure for effectively dealing with abandoned mines situation in South Africa is shown in Figure 3.

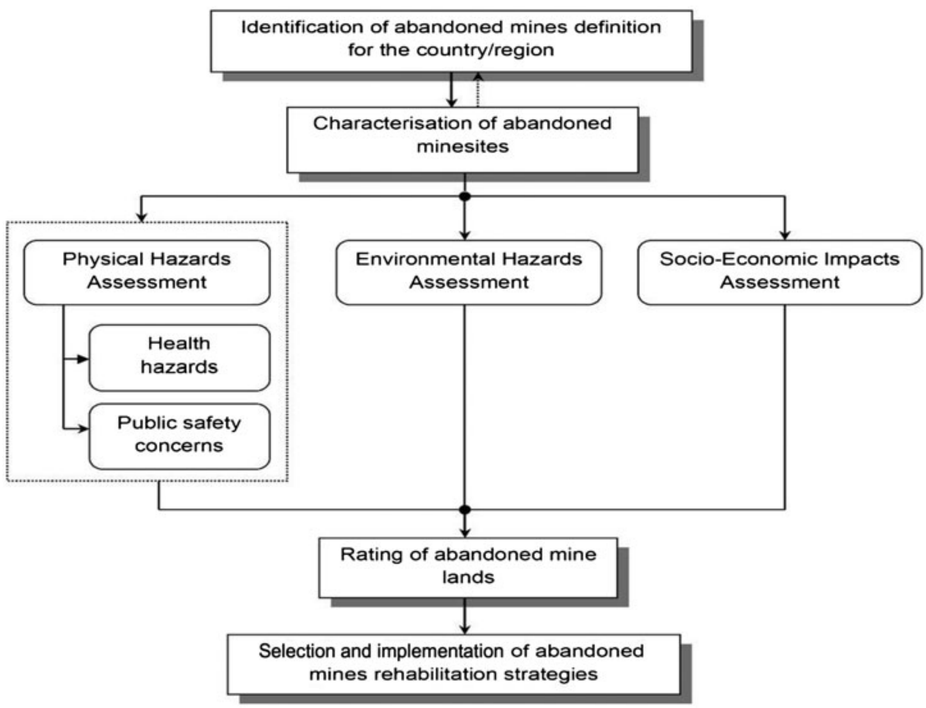

Figure 3. Simplified approach for dealing with abandoned mines.

9. Conclusions

The most important objective of this paper is that the definition of abandoned mines adopted by the country has a significance influence on the work of dealing with these mines. The basic approach of addressing the problems of abandoned mines includes compilation of abandoned mines inventory, characterization of the mine site, prioritisation of rehabilitation efforts and then the selection of appropriate rehabilitation options for abandoned mines. In order to effectively address the issues of abandoned mines in South Africa, an appropriate definition for these mines will have to be agreed upon. The development of consistent abandoned mines rating criteria as well as the rehabilitation cost estimation models that take into account the site-specific situation of the abandoned mines in the country is recommended.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix 1.

Table A1. Environmental aspect of mine closer and rehabilitation options.

Aspect requiring rehabilitation	Rehabilitation approach	Issue	Objectives	Rehabilitation options
Underground mine workings	Physical Stability	• Shaft • Adits • Declines • Subsidence	• Prevent access • Seal • Safety • Stability	• Backfill • Plug openings • Vent water and gas • Infill underground and surface spaces • Surface re-contour
	Chemical Stability	• Mineral Leaching • Acid drainage • Contaminants • Methane	• Clear water • Meet water • Quality regulation • Prevent release	• Flood workings • Plug openings • Remove contaminants • Treat water discharge • Collect and use gas
Surface Mine workings	Physical Stability	• Steep slopes • Unstable faces • Erosion • Hydrology • Safety	• Stable surface • Remove hazards • Control erosion • Clean water	• Re-contour • Re-vegetation • Fence and erect signs • Embankments installation
	Chemical Stability	• Metal leaching • Acid drainage	• Install drainage • Meet water • Quality regulation	• Seal surface • Flood pit • Control hydrology • Treat discharge

(*Continued*)

Table A1. (*Continued*).

Aspect requiring rehabilitation	Rehabilitation approach	Issue	Objectives	Rehabilitation options
Waste rock & spent ore	Physical Stability	• Steep slopes • Unstable faces • Erosion • Drainage • Dust	• Stable surface • Avoid failures, slumps and sediments release	• Site selection • Internal drains • Gentle slopes • Contour surface • Cap • Water ditches • Settling ponds • Establish vegetation • Monitor
	Chemical Stability	• Metal leaching • Acid drainage • Mill reagents • Contaminants	• Clean water	• Dump design • Isolate of reaction material • Cap and re-vegetation • Control drainage • Collect and treat effluent • Monitor
Tailing impoundments	Physical Stability	• Dust • Erosion • Dam wall • Drainage	• Stable surface • Avoid failures and slumps • Control sediment	• Site selection • Dump design • Tailing disposal method • Cap and re-vegetation • Control drainage
	Chemical stability	• Metal leaching • Acid drainage • Mill reagents • Dam structure	• Clean water	• Use chemically stable material in dam wall construction • Pre-treatment of tailings • Cover to control reaction • Form wetland • Divert runoff • Collect and treat effluent • Monitor

Water management	Physical Stability	• Dam walls • Structure • Pipelines • Ditches • Setting ponds • Culverts • Erosion	• Long-time • Safety of • Flood capacity • Prevent blockage • Prevent erosion • Stability • Structures • Free passage of water	• Breach dam • Remove structure • Plug intake and decants • Upgrade flood design • Remove pipes • Fill in ditches • Provide for long-term maintenance • Monitor
	Chemical Stability	• Contaminant of surface and/or ground water	• Clean water	• Remove or prevent contamination • Drain, treat and discharge • Instal barriers • Establish vegetation • Monitor
Mine structures	Physical Stability	• Steep slopes • Unstable faces • Erosion • Drainage • Dust	• Stable surface • Avoid failures, slumps and sediments release	• Site selection • Internal drains • Gentle slopes • Contour surface • Cap • Water ditches • Settling ponds • Establish vegetation • Monitor
	Chemical stability	• Metal leaching • Acid drainage • Mill reagents • Contaminants	• Clean water	• Dump design • Isolate of reaction material • Cap and re-vegetation • Control drainage • Collect and treat effluent • Monitor

(*Continued*)

Table A1. (*Continued*).

Aspect requiring rehabilitation	Rehabilitation approach	Issue	Objectives	Rehabilitation options
Mine infrastructure	Physical Stability	• Building • Equipment • Roads • Airstrips • Services	• Make secure and safe • Clean water	• Disassemble and remove all buildings, equipment and other services • Excavate buried tanks and backfill • Restore drainage • Re-vegetate
	Chemical Stability	• Fuel and chemical storage areas • PCBs and insulation • Explosives • Fuel or oil spill	• Make secure and safe • Clean water	• Remove all unwanted materials • Treat contaminated soil or dispose of in an approved site • Control and treat drainage
Socio-economic mitigation		• Work force	• Re-employment • Relocation	• Assistance with looking for other work and moving • Financial assistance • Counselling
		• Local communities	• Stable economy • Good health • Education facilities	• Regional development plan • Develop local self-sustainable enterprises • Establish foundation or trust fund for essential services • Relocate in-migrants

Source: Ref. [42].