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A Framework for Ranking the Environmental Risk of Abandoned Mines in the State of Minas Gerais/Brazil

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Abstract: Abandoned mines are a major mining liability for the state of Minas Gerais, Brazil. The impacts and risks of abandoned mines are specific to the location and type of ore, but they cover social, economic, and cultural aspects. A central element of an abandoned mine management policy is the definition of a methodology to identify and rank characteristics of abandoned mines that pose a risk to the environment and society. This article presents a methodology for the ranking of environmental risks for abandoned mines in the state of Minas Gerais based on different evaluation factors of their external effects on the environment, safety, the population and surrounding areas, heritage and the landscape. The environmental risk of the abandoned mine area was generated to establish the "Abandoned Mine Area Environmental Risk Hierarchy". To achieve this a multi-criteria analysis (using the Analytical Hierarchy Process (AHP)) was adopted with each preponderant factor being compared and measured. The results show that the use this framework can support in the decision-making process of an environmental agency for developing the intervention aimed at situations of greater gravity, which, ultimately, may require the use of public resources to reduce risks.

Keywords: abandoned mines; risk assessment; hierarchy; mine closure; environmental reclamation

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1. Introduction

Internationally and in Brazil, there is no clear or widely accepted definition for what is an abandoned or orphan mine. The environmental legislation of the state of Minas Gerais defines an abandoned mine as one with an inactive mining operation and mineral treatment, with no forecast of restarting the activity, without implemented environmental control or monitoring measures, and with characteristics of abandonment. Furthermore, in this case, the closing process is incomplete or absent [1].

Abandoned mines represent an environmental liability of great importance for countries with a mineral vocation, and the causes of the emergence of abandoned mines are complex and may be unique to one location [2–5]. However, abandonment results from failures in the mine closure planning throughout the operation of the activity, including the following: unachievable goals; insufficient legal and institutional frameworks to demand the implementation of closure actions, in cooperation with the impacted communities; the inability of the regulatory agency to demand progressive recovery actions in the environmental licensing; economic reasons, mainly related to the drop in the prices of mineral raw materials and the loss of a market for certain goods; and the underestimation of expected costs and deadlines for closing or lack of provision for the closing stages.

Institutions and authors [4,6–8] indicate the need for a strategic structure for the management of abandoned mines, divided into five main elements: (1) inventory and data management; (2) an understanding of the responsibilities and associated risks; (3) intervention performance reports; (4) the standardization of processes and methodologies and (5) the sharing of obligations between agencies.

One of the central elements of an abandoned mine management policy is the understanding of the social, environmental, and safety risks associated with these areas. This understanding allows the environmental agency to establish a methodology for ranking the risks, while valuing the assets and opportunities that the mine may have, in order to prioritize the allocation of human and financial resources for the recovery of those with greater risks. Strategies for the systematic identification and prioritization of abandoned mines suitable for environmental restoration, based on robust scientific evidence, are essential for defending the use of public funds [9,10].

The complexity of the effects of areas degraded by mining and other potentially polluting activities, which include several dimensions, has been the object of several scientific studies, particularly multi-criteria analysis [11–13]. In parallel, agencies responsible for environmental and mineral management also seek mechanisms for surveying environmental liabilities and damages, ranking risks, and defining priority areas for intervention [8,14–20].

The risk assessment process identifies the characteristics of the abandoned mine that pose the greatest environmental or safety risk to be considered in the prioritization assessment [14,21]. The risk assessment process should support the planning of works and reports on risk mitigation and should function as an adaptive management strategy by which risks are identified, classified, and then progressively managed into decision-making priorities [8].

In the state of Minas Gerais, the environmental agency made the first effort to inventory and rank the paralyzed and abandoned mines, in terms of their potential environmental risk, through the First Register of Paralyzed and Abandoned Mines in the State of Minas Gerais [1]. Unfortunately, this register was not updated until the year 2021. Four hundred mines were ranked, based on a methodology that crossed the criterion of “environmental risk of the mined area”, considering 10 variables for the characterization of each mine and its surroundings, as defined by the environmental agency, with the criterion “natural vulnerability” of the region where the mine is located obtained from the state’s ecological economic zoning [22] to establish the “final environmental vulnerability” of each mine, according to five classification grades. According to FEAM [17], areas with a very high “final environmental vulnerability” are those where mine operations have caused a significant environmental impact in a location that has low resilience due to a high or very high natural vulnerability.

This article presents a new methodology for ranking the environmental risks for abandoned mines, based on attributes related to social and environmental impacts related to the following four scenarios: environment; safety; population and surrounding areas; and heritage and landscape. The methodology is based on the analytical hierarchy process (AHP), developed by Saaty [23], to establish the environmental risk of each mine and had, as a database, a group of abandoned mines managed by the environmental agency of the state of Minas Gerais.

The proposal of the “Ranking of the Environmental Risk of the Abandoned Mined Area” in the state of Minas Gerais aims to contribute to the implementation of a program for the prevention and management of abandoned mines in the state of Minas Gerais, an integral part of a mine closure policy. In addition to that, the proposed ranking system seeks to identify the risks and opportunities of abandoned or orphan mines, support decision-making by the environmental agency to hold the polluter financially accountable, implement emergency actions depending on the seriousness of the situation, develop risk mitigation measures and options based on priority, and seek partnerships for the recovery of orphan mines.

2. Materials and Methods

The Analytic Hierarchy Process (AHP), developed by Saaty [23], is one of the best known and most used in multi-criteria analysis. AHP involves identifying a decision problem and then decomposing it into a hierarchy of smaller and simpler “sub-problems”, where the sub-problem can be analyzed independently, without losing the focus on the decision problem.

AHP is based on three basic principles, which constitute the three steps of the process: (1) the principle of decomposition, which consists of breaking complex problems into less complex "sub-problems" in a hierarchical decision model; (2) the principle of comparative judgment, which consists of the comparative judgment of pairs of criteria or alternatives, from a pre-defined scale of importance, instead of trying to assign arbitrary weights simultaneously to each criterion or classification in all alternatives; and (3) the principle of hierarchical composition, which consists of appropriately aggregating the values determined for each criterion and sub-criterion, based on their respective weights until a final "classification" for the studied objective is determined [24].

For Windy and Saaty [25], prioritizing factors of lesser importance in relation to the objective depends only on a sequence of peer comparisons, with or without feedback between levels. This was found to be the rational way to deal with the judgments. Through these pairwise comparisons, the priorities calculated by the AHP capture subjective and objective measures and demonstrate the intensity of dominance of one criterion over another or of one alternative over another.

The steps involved in the AHP method, developed in this research, for ranking the environmental risk of the abandoned mined area are presented in Figure 1 and detailed below:

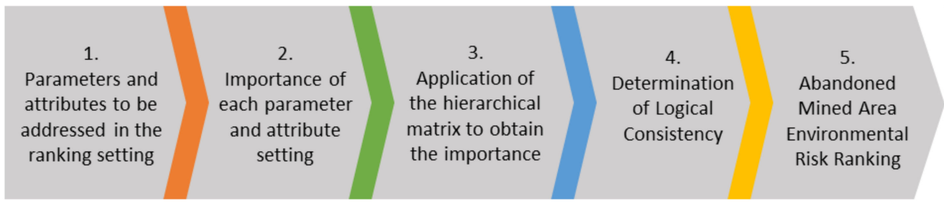

Figure 1. Steps involved in the AHP method.

2.1. Category Setting and Attributes to Be Addressed in the Hierarchy

An effective risk assessment program is dependent on a detailed data collection system. Key risks may include, but are not limited to, site safety and mine characteristics, environmental issues (including impacts on flora and fauna), contamination, acid mine drainage, property, health, and socio-political risks [14].

The selection of categories and attributes that will have their importance weights defined by the AHP method was performed based on the following: the information presented in the First Register of Paralyzed and Abandoned Mines [17]; the verification of the main environmental impacts existing in the group of abandoned mines in the state of Minas Gerais studied in this research; and the evaluation of other methodologies for ranking the risks of abandoned mines adopted in other countries.

2.2. Definition of the Importance of Each Category and Attribute

From the definition of categories and respective attributes that will be used in the ranking of environmental risk, the step of defining the importance of each category and attribute is carried out. This step aims to support the valuation of grades and the reduction of subjectivity during judgments and quantification. The comparisons represent, respectively, the relevance of a category of "Row A" related to the category of "Column A", of the so-called decision matrix.

The variables are all compared to each other, and the weights of importance are thus assigned. Saaty [23] assigns weighting values ranging from "equal importance" to "absolute importance" on the scale, determining the relative importance of one alternative over another. The Saaty Ratio Scale has a predefined scale of 1 to 9, where the value 1 is the minimum, and 9 is the maximum importance of one factor over the other, as shown in Table 1.

Table 1. Saaty's fundamental scale. Source: Saaty (1991).

Importance Intensity	Definition	Explanation
1	Equal importance	Both activities contribute equally to the goal.
3	Weak importance	Experience and judgment slightly favor one alternative over the other.
5	Strong importance	Experience and judgment strongly favor one alternative over another.
7	Very strong importance	One activity is strongly favored over another; its dominance of importance is demonstrated in practice.
9	Absolute Importance	Evidence favors one activity over another with the highest degree of certainty.
2, 4, 6 and 8	Intermediate values	When looking for a condition and compromise between two definitions.

Disregarding the comparisons between the categories themselves, which in this case will be identified by the main diagonal of the decision matrix and will represent importance 1, it is concluded that only half of the comparisons need to be made (identified by the letters from a to f).

In this research and as shown in Table 2, the upper half of the main diagonal was freely proposed, since the lower part consists of reciprocal comparisons. It is also noteworthy that the most important element of the comparison will always be used as an integer value, and the least relevant, therefore, as its inverse, will always be less than 1.

Table 2. Decision matrix or comparative square matrix.

	Category 1	Category 2	Category 3	Category 4
Category 1	1	a	b	c
Category 2	1/a	1	d	e
Category 3	1/b	1/d	1	f
Category 4	1/c	1/e	1/f	1

For the purpose of this research, it is identified that the judgments are based, summarily, on the answer to the following question: "To rank the environmental risk of an abandoned mine, which of these two categories or attributes is more important and what is the intensity of it in relation to the other?"

2.3. Application of the Hierarchical Matrix to Obtain the Importance and Determine Logical Consistency

After filling out the decision matrix, as shown in Table 3, it is necessary to calculate the relative weight vector or eigenvector (P) or, also known, the matrix's priority vector. This vector has a fundamental role since it will provide the judgment priority, in terms of importance, of the (n) evaluated categories.

Table 3. Average random index of the AHP. Source: Saaty (1991).

Order (n)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
ICA	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

As proposed by Saaty [23], for the calculation of that eigenvector, firstly, each evaluation will be divided by the sum of the terms of the column in which the judgment is found. The matrix resulting from this process will be called the normalized matrix [A']. Then, calculating the sum of the values of each of the lines of the normalized matrix [A'] is recommended, which, after being added, should be divided by the total number of categories (n), to obtain the relative weight, or eigenvector (FOR).

In order to have a matrix consistency and to present adequate results, it is necessary that, based on a quantity of data, a series of calculations based on the methodology proposed by Saaty [25] be developed. Such calculations should be performed to find acceptable values for two specific categories: the consistency index (*CI*) and the consistency quotient (*QC*).

From the relative weight vector (*P*) obtained and the maximum eigenvalue (λ *max*), it is necessary to verify the consistency rate (*CI*) of the matrix [A] of judgments. This rate is given by multiplying the initial matrix [A] by the weight eigenvector (*P*), resulting in a new vector (AP). The consistency index (*CI*) of the comparative matrix is calculated from Equation (1).

$$CI = \frac{\lambda\ max - n}{n - 1} \tag{1}$$

where n is the number of categories under analysis and λ *max* is the maximum eigenvalue of matrix [A].

To obtain the maximum eigenvalue (λ *max*), it is necessary to produce a new vector (AP), from the multiplication of the initial matrix [A] by the weight eigenvector (*P*). Next, the arithmetic mean of this new vector (AP) is divided, once again, by the eigenvector (*P*) (Equation (2)).

$$\lambda\ max = media\ do\ vetor\ \frac{(\mathrm{AP})}{(P)} \tag{2}$$

where AP is the number of categories under analysis and *P* is the relative weight vector.

Then, the vector values (AP) are added and divided by the number of categories (n) initially considered, obtaining the maximum eigenvalue (λ *max*) of the initial matrix [A]. It is observed that the closer the maximum eigenvalue (λ *max)* is to the number (n) of components, the more consistent the desired results will be.

Finally, from the previous category, it is possible to calculate the consistency index (CI) of the comparative matrix [A] (Equation (1)). The judgments with consistency indices (CI) less than 0.1 are considered acceptable and, therefore, the continuation of the calculations in the methodology under study is indicated. For indexes greater than 0.1, it is recommended to reevaluate the categories and respective weight assignments (judgments), until consistency decreases, and an acceptable level is reached.

To guarantee the consistency of a matrix, it is also emphasized that the value of λ *max* must always be greater than the number (n) of categories under analysis and that the closer to (n), the greater the consistency of the evaluated matrix.

In addition to the two consistency-checking methods, Saaty [19] finally proposes yet another resource for evaluating the consistency of judgment matrices, also known as consistency quotient (*QC*) or consistency ratio, which is determined by equation (3).

$$QC = \frac{CI}{ICA\ para\ n} \tag{3}$$

where *CI* is the consistency index and *ICA* is the random consistency index.

This last method relates the consistency index (*CI*) to a random consistency index (*ICA*), which is a random dimensionless number, chosen according to the sample size (number "n" of selected categories), as shown in Table 3. Generally, values for the consistency quotient (*QC*) equal to or less than 0.1 are adopted as acceptable.

2.4. Abandoned Mine Area Environmental Risk Ranking

To quantify the environmental risk, the weights (Pi) are used, obtained through the auto vector (*P*), as a function of the weighted weight of each selected attribute corrected by the weight of the category to which the attribute is linked. After this correction, the final weight of each attribute is multiplied by the score of the "socio-environmental characterization criterion", which represents the current situation of the mine referring to that attribute, with scores ranging from 0 to 1.0 (best in the worst situation), as shown in Figure 2. The sum of all scores will produce the final score that represents the "Abandoned Mined Area Environmental Risk Ranking".

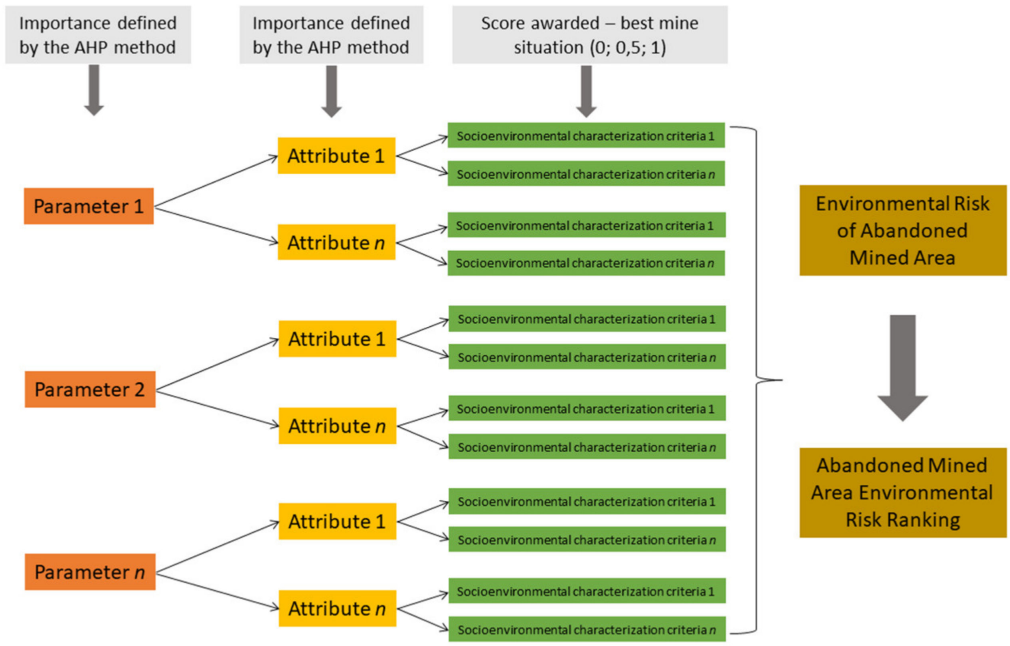

Figure 2. Flow for obtaining the environmental risk rank of the abandoned mine area.

For a clearer presentation of the results, in addition to the environmental risk of the abandoned mine area assigned to each mine to rank the group of mines managed by the environmental agency, the information must be organized into categories so that they represent the degree of environmental risk of the mines. The definition of these degrees does not concern the AHP method but is a way to complement it and support the decision-making of the environmental agency.

3. Results and Discussion

A comprehensive assessment of the First Register of Paralyzed and Abandoned Mines in the state of Minas Gerais and of the field reports was conducted to assess what information will be used for the risk assessment and ranking of abandoned mines [17]. In addition, other methodologies for ranking the risks of abandoned mines adopted in other countries were verified [8,15–20,24]. Twenty-one (21) attributes were defined and distributed into the following four categories that should be considered when assessing an abandoned mine: "environment"; "safety"; "population and surroundings" and "heritage and landscape". The description of each of the attributes is presented in Table 4.

Given the AHP method concerning the analysis of the categories, it was first necessary to obtain the original comparison matrix [A] (Table 5) and then the normalized matrix [A'], that is, a derivative of the original comparative matrix [A] (Table 6). To do this, each term in the initial matrix was divided by the sum of all terms in the corresponding column, and then all terms in each of the rows were added. The results of the sum of each of these lines were divided by the total number of categories (n), in this case, four, to obtain the weight vector or eigenvector (P), (Table 6).

Table 4. Categories, attributes, and criteria for environmental characterization for ranking the environmental risk of the abandoned mined area.

Category	Attribute	Environmental Characterization Criteria	Value	Description
Environment	Size of the impacted area	Up to 5000 m^2 5000 a 10,000 m^2 Bigger than 10,000 m^2	0 0.5 1	Area directly impacted by mining activities. This variable does not consider the mining right area, but the area that is impacted.
	Approximate time of abandonment	Less than 2 years From 2 to 10 years Greater than 10 years or indefinite	0 0.5 1	Year in which the mine stopped or abandoned activities at the site. When it is not possible to identify the year, the time is considered as "indefinite".
	Existence of a mining tailings dam	No or uncharacterized Yes, Class 1 or Class 2 Yes, Class 3	0 0.5 1	Any structure (dam, damming, dike, or similar) that forms a retaining wall for tailings, waste, based on the classification of environmental damage: Class I; Class II; Class III or that is already uncharacterized, according to Law No. 23.291/2019.
	Existence of unstable tailings/sterile piles	No Yes	0 1	The mineral activity produces two by-products, sterile and tailings, which can be placed in piles. The main environmental impacts from these structures are the alteration of the topographic surface and the landscape, loss of superficial soils, instability of cut or embankment slopes, alteration of water bodies, and groundwater levels and exposure of areas to erosion and silting.
	Existence of a lake formed in cave or mine front	No Yes, less than 3 m deep Yes, more than 3 m deep	0 0.5 1	The pits and mine fronts in mines without operation are invaded by surface and subsurface waters, configuring the formation of lakes, characterized by different volumes and conditions.
	Existence of erosive processes and siltation of surface water bodies	No Yes, small to medium degree Yes, high degree	0 0.5 1	Erosion is a very complex phenomenon since it involves the direct or indirect action of several environmental factors, in addition to human interference. Silting of surface water bodies is the process in which a watercourse is affected by the accumulation of sediments or materials from the mine area, which results in excess material on its bed, with impacts on biota, quality of water, and visual impact.
	Potential for soil or groundwater contamination	No Yes	0 1	Environmental contamination is the presence of chemical substances in environment, resulting from human activities, in concentrations such that they cause, or may cause damage to human health and the environment.
	Natural regeneration processes	Advanced level Intermediate level No	0 0.5 1	Natural regeneration is a set of processes in which vegetation settles in a degraded area without them having been introduced by human action.
Safety	Area fencing	Yes No	0 1	Existence of fencing around the boundaries of the mine's property, preventing invasions and inappropriate uses.
	Area Signaling	Yes No	0 1	Existence of signs informing about the mine's situation and potential risks, preventing invasions and inappropriate uses.
	Unused and/or abandoned building	No Yes	0 1	Existence of facilities that were used in the mine's activities, such as maintenance and loading yards for trucks and sheds with machinery and administrative facilities, such as an office, restrooms, and cafeteria previously used by employees. Fuel filling areas or fuel tanks.

Table 4. *Cont.*

Category	Attribute	Environmental Characterization Criteria	Value	Description
	Unused and/or abandoned equipment	No Yes	0 1	Existence of equipment that was used in the mine's activities, as machinery, conveyor belts, ornamental stone cutting equipment, trucks, tractors, wheel loaders, and pumps. In ornamental rock mines and quarries, the existence of drag winches is common, and in mines extracting sand and diamond, the existence of dredges.
	Abandoned solid waste	No Yes, non-hazardous waste Yes, hazardous waste	0 0.5 1	Solid waste is discarded material, substance, object, or property resulting from human activities in society, whose final destination is proceeded, proposed to proceed or is obliged to proceed, in solid or semi-solid states, as well as gases contained in containers and liquids whose particularities make its release into the public sewer system or water bodies unfeasible, or require technical or economically unfeasible solutions for that given the best available technology.
Population and surroundings	Irregular use of the mine without authorization from the government	No Yes, without production impacts Yes, producing impacts	0 0.5 1	Use of the mined area by third parties, for the most diverse purposes, mainly related to illegal extraction, for the clandestine disposal of residues, use for leisure and tourism, and agricultural activities.
	Near Conservation Unit-UC (buffer zone)	Outside the buffer zone of Integral Protection CU and Sustainable Use CU Within the Sustainable Use CU buffer zone Within the Full Protection CU buffer zone	0 0.5 1	According to Resolution no. 428/2010, the buffer zone is defined as a band of 3000 m, starting from the boundary of the Conservation Unit-UC, for a project with a significant environmental impact, except for the Private Natural Heritage Reserve-RPPN and the Environmental Protection Area-APA. In this way, an assessment was carried out as to whether the project was within the buffer zone of an Integral Protection CU or a Sustainable Use CU.
	Distance from watercourse APP	Within the Full Protection CU buffer zone Proximity below 30 m to the watercourse	0 1	According to Law no. 12.651/2012, which defines Permanent Preservation Area (PPA), 30 m are considered for watercourses less than 10 m wide. This category was considered as being the most restrictive.
	Proximity to urban area	No: Outside 1 km radius Yes: Within 1 km radius	0 1	The urban area was defined based on IBGE census sectors (IBGE/CENSO 2010), with the sectors of the "Urban" category being considered for the Registry. Thus, the urban situation is assumed to be areas corresponding to cities (municipal seats), towns (district seats), or isolated urban areas.
	Proximity to traditional peoples and communities	No: Outside 1 km radius Yes: Within 1 km radius	0 1	Traditional Peoples and Communities are defined as: "culturally differentiated groups that recognize themselves as such, that have their forms of social organization, that occupy and use territories and natural resources as a condition for their cultural, social, religious, ancestral reproduction and economic, using knowledge, innovations, and practices generated and transmitted by tradition".

Table 4. *Cont.*

Category	Attribute	Environmental Characterization Criteria	Value	Description
Heritage and landscape	Important mining structures/modes to be preserved	No Yes	0 1	In abandoned mines, there may be structures and equipment that can be used for society to acquire knowledge about mining in the state of Minas Gerais
	Important features for geotourism	No Yes	0 1	In paralyzed and abandoned mines, there may be characteristics that can be used to learn about aspects of the geology and geomorphology of the region and the state, contributing to geotourism
	Visual and landscape impact	No Yes, intermediate Yes, advanced	0 0.5 1	The impacts linked to the alteration of the landscape are the opening of mine fronts or wells, tailings and sterile piles, siltation of valleys and water courses by erosion, devastated areas or exposed soil.

Table 5. Square matrix for parity judgment of the evaluation categories proposed in this study.

Mine Environmental Risk	Environment	Safety	Population	Heritage and Landscape
Environment	1	1	3	7
Safety	1	1	3	7
Population	1/3	1/3	1	5
Heritage and landscape	1/7	1/7	1/5	1
TOTAL (quantity)	2.48	2.48	7.2	20.0

Table 6. Normalized matrix [A′] and eigenvector (*P*).

Mine Environmental Risk	Environment	Safety	Population	Heritage and LANDSCAPE	Eigenvector (*P*)
Environment	0.404	0.404	0.417	0.350	0.394
Safety	0.404	0.404	0.417	0.350	0.394
Population	0.135	0.135	0.139	0.250	0.165
Heritage and landscape	0.058	0.058	0.028	0.050	0.048

In general, the categories had the following weight relationship:

1. "Impacts relating to the environment" and "Impacts relating to safety" are equally important.
2. "Impacts relating to the environment" is a little more important than "Impacts on the population and surrounding areas".
3. "Impacts relating to the environment" is much more important than "Impacts relating to heritage and landscape".
4. "Impacts on population and surrounding areas" is more important than "Impacts related to heritage and landscape".

The relationship of importance between the various categories was given based on the authors' experience in the management of abandoned mines at the Environmental Agency of the state of Minas Gerais and on the preparation of the First Survey of Abandoned Mines in the State of Minas Gerais (FEAM, 2016), equivalent to the methodologies adopted by other countries, such as Chile, Australia and Portugal (SERNAGEOMIN, 2007; MCMPR and MCA, 2010; MATOS et al. 2018) for the ranking of risks in abandoned mines. Furthermore, these references supported the authors in selecting the criteria and attributes with their respective grades, weights, and importance in the proposed methodology.

To obtain the maximum eigenvalue ($\lambda\ max$), the new vector (AP) was calculated and, subsequently, the arithmetic mean of this new vector (AP) was divided by the eigenvector (*P*), as shown in Table 7.

Table 7. Vector Calculation (AP) to support the calculation of $\lambda\ max$.

Mine Environmental Risk	Vector (AP)	Vector (AP)/Eigenvector (*P*)
Environment	1.619	4.113
Safety	1.619	4.113
Population	0.668	4.062
Heritage and landscape	0.194	4.010

Finally, the consistency check of the comparison matrix of the four categories (judgments), conducted through the methods Consistency Index (CI) and Consistency Quotient (*QC*), is presented in Table 8.

Table 8. CI and *QC* calculation to determine logical consistency.

Evaluated Indicator	Value
λ *max*	4.075
CI	0.025
QC	0.028

Based on the AHP methodology and the values obtained for λ *max*, CI, and *QC* (less than 0.1), it is stated that the category matrix can be ordered hierarchically and, therefore, that the importance of the vector obtained is considered acceptable. The methodology allowed us to establish, among the chosen criteria, which will have the greatest influence in determining the environmental risk of the abandoned mine, as shown in Table 9.

Table 9. Distribution importance of categories for assessing the environmental risk of an abandoned mine.

Impact Assessment Categories	Importance
Environment	39%
Safety	39%
Population	16%
Heritage and landscape	5%

In the same way that the AHP methodology was used to determine the importance of the categories in the contribution to the environmental risk of an abandoned mine, it was applied to define the importance of each attribute by category, allowing it to be possible to assess the importance of each attribute, for each of the four categories analyzed.

As for the categories, the analysis of the logical consistency of the attribute weights respected the values for λ *max*, *CI*, and *QC* (less than 0.1), it can be said that the attribute matrices per category can be ordered hierarchically and, therefore, that the obtained weight vector is considered acceptable.

From the calculation of the importance of each attribute, the attributes were corrected according to the weight of the categories linked to them to reflect their importance in defining the final score for the environmental risk of the abandoned mined area.

The ranking performed in this research allowed us to establish, among all the chosen attributes, which will have the greatest influence in determining the environmental risk of the abandoned mined area, as well as the attributes with less significance, as shown in Table 10. Figure 3 shows the five attributes with the greatest impact in the evaluation, that is, they present a higher priority vector. On the other hand, Figure 4 presents the five attributes with the lowest impact on the assessment, which will influence to a lesser extent the determination of the environmental risk of the abandoned mine.

Table 10. Distributive importance of attributes for assessing the environmental risk of the abandoned mined area.

Category	Attribute	Importance	Importance Corrected from Associated Category
Environment (Grade 0.394)	Existence of a mining tailings dam	0.3297	0.1298
	Potential for soil or groundwater contamination	0.2254	0.0887
	Existence of erosive processes and siltation of surface water bodies	0.1453	0.0572
	Existence of unstable tailings/sterile piles	0.1218	0.0479
	Existence of a lake formed in cave or mine front	0.0656	0.0258
	Size of impacted area	0.0575	0.0226
	Approximate time of abandonment	0.0332	0.0131
	Occurrence of natural regeneration processes	0.0216	0.0085
Safety (Grade 0.394)	Abandoned solid waste	0.3977	0.1565
	Unused and/or abandoned equipment	0.2489	0.0980
	Unused and/or abandoned building	0.1896	0.0746
	Area fencing	0.1006	0.0396
	Area Signaling	0.0632	0.0249
Population and surrounding areas (Grade 0.165)	Irregular use of the mine without authorization from the government	0.5276	0.0868
	Distance from watercourse APP	0.2208	0.0363
	Proximity to urban area	0.1029	0.0169
	Proximity to traditional peoples and communities	0.1029	0.0169
	Near Conservation Unit-UC (buffer zone)	0.0456	0.0075
Heritage and landscape (Grade 0.048)	Important features for geotourism	0.2605	0.0126
	Visual and landscape impact	0.6333	0.0306
	Important mining structures/modes to be preserved	0.1062	0.0051

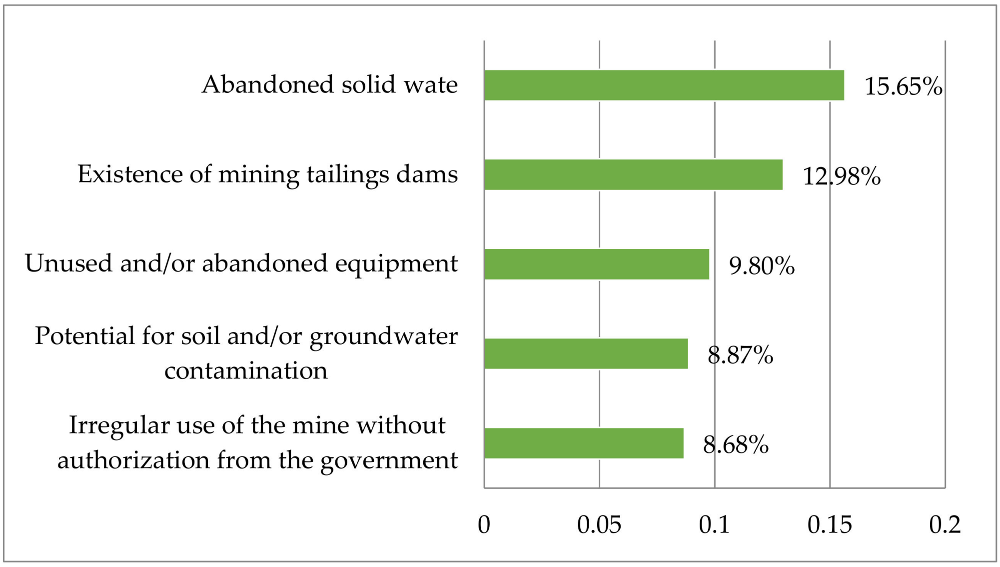

Figure 3. Importance attributed, highlighting the most relevant categories for determining the environmental risk of the abandoned mine.

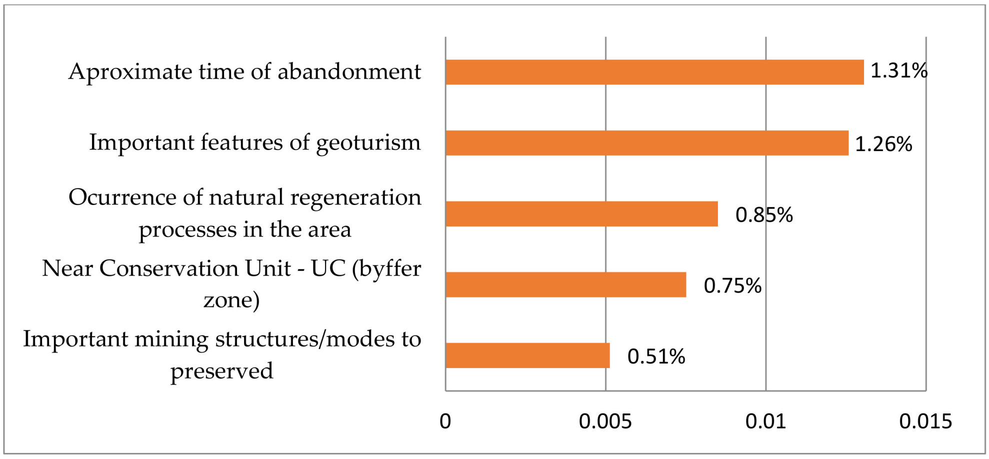

Figure 4. Attributed importance with emphasis on categories of lesser relevance for determining the environmental risk of the abandoned mine.

To finalize the calculation of the environmental risk of each mine, in possession of the weights of the attributes, the notes of the environmental characterization criteria raised for each mine, according to the distribution presented in Table 4, must be applied, producing the final value for the environmental risk of the abandoned mine.

Once the environmental risk value of each abandoned mine has been determined, it is important to keep in mind that the main objective is the "Abandoned Mined Area Environmental Risk Ranking", with the assessment of each mine's value simultaneously, pointing out which are the most critical mines, with a high associated environmental risk, that will require emergency government actions.

As a complement to the "Abandoned Mined Area Environmental Risk Hierarchy", aiming at a clearer presentation of the results, the information can be organized into categories that represent the degree of risk, which can range from 0 to 1, as shown in Table 11.

Table 11. Environmental risk category of the abandoned mined area.

Grade Range	Mine Environmental Risk Category
$0 \leq$ Grade < 0.2	Very low
$0.2 \leq$ Grade < 0.4	Low
$0.4 \leq$ Grade < 0.6	Average
$0.6 \leq$ Grade < 0.8	High
$0.8 \leq$ Grade < 1	Very high

4. Conclusions

In Brazil, the state of Minas Gerais, like other states and provinces in several countries with a mining vocation, has a large environmental liability linked to abandoned mines, which results in different scales of risks to the environment and public health. These risks and the complexity of measuring and minimizing their effects require public bodies to establish guidelines and robust identification, ranking, management, accountability, and monitoring processes.

The proposal presented in this article was developed for a risk assessment framework based on the definition of attributes and their respective weights of importance for the composition of the final environmental risk of an abandoned mine, distributed in the following four scenarios: environment; safety; population and surrounding areas; and heritage and landscape, with the correlation of the environmental characterization criteria raised for each mine.

The methodology was based on evidence and experiences of the author and employees of the environmental agency to ensure that the main impacts and risks were identified and quantified to justify the need for accountability of the paying polluter and environmental recovery, supporting the implementation of a prevention program in the management of abandoned mines, within the scope of mine closure management in the state of Minas Gerais. The hierarchy proposal presented in this research allows the comparison of mines (or group of mines), the comparison of the importance of attributes for a single mine, or the verification of attributes that systematically present risks in abandoned mines.

This methodology was tested using the database of abandoned mines created by the environmental agency of the state of Minas Gerais and proved to be efficient in determining individual environmental risks, in the ranking of mines and in identifying mines that required priority government action, considering a scenario of economic restrictions, for the adoption of environmental recovery measures. Furthermore, the methodology, as well as the results, were audited to minimize the errors/failures experienced in the field work. A paper dealing with these results will be submitted for publication shortly. Furthermore, the hierarchy of mines made it possible to identify values and opportunities related to the industrial heritage of some abandoned mines.

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