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APPLICATION OF A SPATIAL MULTICRITERY DECISION ANALYSIS METHODOLOGY FOR SELECTION OF AREAS FOR A GEOLOGICAL REPOSITORY IN ESPÍRITO SANTO

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ABSTRACT

The production of electrical energy through nuclear power plants results in the production of nuclear waste that must be disposed of safely. The most accepted method for the disposal of these tailings is through the use of deep geological repositories. So far, Brazil does not have specific legislation for the selection of suitable locations for this type of repository. The Spatial Multicriteria Decision Analysis methodology aims to identify and classify regions of interest for the implementation of a project within the geographic space. The method is suitable for projects whose decision-making process encompasses a wide variety of factors and in a wide geographic space. In this context, the process of selecting sites for the implementation of a deep geological repository, which must reconcile long-term security, social/economic/environmental factors, and technical feasibility, is an ideal case for its application. This work used this method in the Brazilian State of Espírito Santo. Geospatial data from different sources and a data classification system were used to generate numerical parameters. The combination of these parameters results in a map of suitability for the geological repository. Regions of interest have been identified for further detailed studies in the northern part of the State associated with the Medina-Maristela unit, a domain of undeformed granite complexes with poor soils, low hydrogeological potential, and granites of low commercial interest.

1. INTRODUCTION

The first Brazilian nuclear power plant, Angra 1, completed 36 years of commercial operation and its owner, Eletrobras Electronuclear, is currently applying for an extension of its operating license up to 2044 [1]. However, the destiny of the spent nuclear fuel (SF) from the Brazilian nuclear power plants (NPPs), Angra 1 and Angra 2 is uncertain. The management of SF is a national pending issue, being the current policy to store it on the colling pools inside the NPPs and, in the future, to store it with dry storage technology until a decision about the configuration of the Brazilian nuclear fuel cycle is taken.

Nevertheless, regardless of the nuclear fuel cycle configuration high-level waste (HLW) and SF still need to be disposed of safely. Currently, deep geological disposal is accepted as the only feasible method to ensure the very long-term safety of those wastes [2, 3]. This disposal method is based on the construction of underground cavity openings at depths of approximately 500 m and "burying" the SF. The excavated rocks are considered the last containment barriers in the event of accidents. In general, host rocks must have low permeability and porosity while other properties may vary to a greater degree. As each national territory has one or more types of rocks suitable for receiving the repository, the choice of rock depends on several factors, such as the geotectonic environment, hydrogeological environment, land uses, presence of minerals, etc. The rock formations studied include salt formations (Germany), clays (France and Belgium), and hard metamorphic or granite (Finland and Sweden) [3].

Given the complexity involved in the construction and operation of the repositories against the criteria of safety and viability - technical, social, environmental, and economic - the choice of potential sites for the construction of the repository, which meet all the criteria, is an arduous and long task. To simplify and optimize the selection process, it is possible to use a combination of multicriteria analysis and the Geographic Information System (GIS). The result of these methods is the indication, on a map, of the regional suitability for the installation of a geological repository.

However, Brazil lacks a specific rule available to the SF by the responsible government agency, the National Nuclear Energy Commission (CNEN). This in practice means that there are no national criteria for choosing the type of host rock or for the process of choosing the repository site. Thus, research related to the topic is still incipient in the country, given the impossibility of in-depth studies without clear criteria.

To date, there are only three works, known to the authors, aimed at selecting sites for the construction of a national SF repository. Martins [4] proposed an area selection methodology based on a repository model that uses hard rocks as hosts and applied the method to the state of Rio de Janeiro. Silva *et al* [5][1], was building a geospatial database to be used for a site selection in the state of Rio de Janeiro. Jonusan *et al* [6] [2] applied the method proposed by Martins for the state of Minas Gerais and identified areas of interest in the state.

This paper aims to apply the methodology proposed by Martins [4] to the state of Espírito Santo, previously applied to other states in the Brazilian Southwest, and to expand the number of sites studied for a future Brazilian SF repository. Geospatial data available from Brazilian government agencies – Brazilian Geological Service (CPRM) [7], Embrapa [8], National Department of Transport Infrastructure [9], and Brazilian Institute of Geography and Statistics (IBGE) [10] – were used for the creation of a map of the suitability index for the construction of a geological repository. The results show that Espírito Santo has areas considered as good and meritorious for further investigation.

2. METHODOLOGY

This work used the methodology proposed by Martins [4] to find, in the State of Minas Gerais, the most suitable region for the installation of a geological repository. This method is a combination of multicriteria decision analysis and spatial analysis using GIS for mapping the most suitable locations for further studies on the installation of the repository.

The methodology of multicriteria decision analysis, through the Hierarchical Decision Analysis (AHP) procedure, involves, briefly, the definition of goals to be achieved, decision group, evaluation criteria (comparison), and results [4]. The great advantage is the possibility of evaluating a set of alternatives, based on conflicting criteria. The GIS makes it possible to analyze the best location for a project. The combination of these methods results in a set of data/alternatives spatially ordered to aid decision-making [4].

2.1 Geological description of the study area

Espírito Santo is a state in southeastern Brazil, having as limits the states of Minas Gerais (west), Bahia (north), Rio de Janeiro (south), and the Atlantic Ocean (east). The state is completely inserted in the evolutionary geotectonic context of the Mantiqueira province (Araçuaí Mobile Belt), in which it is dated to the Neoproterozoic - Cambrian age, having as its base Archean blocks agglutinated between 2.2 to 2.0 $x10^9$ years. Neoproterozoic to Cambrian igneous and metamorphic rocks represents about two-thirds of the territory. The rest is composed of phanerozoic covers [7].

The evolutionary history of Araçuai Orogen is the most principal factor for understanding the geology of the state of Espírito Santo. It has two major evolutionary stages, which are related to the precursor stage of the basin and the orogenic stage [11, 12]. Concerning the precursor stage of the basin, three processes are related, the formation of the continental pre-rift, passive continental margin, and the formation of the ocean [11, 12].

In the orogenic stage, four processes are identified in the event, pre-collisional (subduction of the oceanic lithosphere and generation of calcium-alkaline magmatic arc), sin-collisional (crustal thickening, partial fusion, and generation of type S magma), late collisional (generation of type S granites by partial adiabatic melting) and post-collisional [13].

With the opening of the Atlantic Ocean (Jurassic at the end of the Cretaceous), the Orógeno Araçuaí underwent a separation process, in which it provided the African part of the orogen (Orogen West Congo). Thus, originating the basins of passive margins and the deposition of coverings at both ends of the ocean [14]

The Orógeno Araçuaí is mostly composed of orthogneisses, exemplified by the complexes Guanhães, Gouveia, Porteirinha, Mantiqueira, Juiz de Fora among others. The outcrops related to the base (Archaean - Paleoproterozoic) of the orogen, are only exposed in a small area on the border with the state of Minas Gerais [11, 12].

2.2. Criteria and Attributes

The criteria and weights used in this work were adapted from Martins [4]. The criteria are classified and standardized on a numerical scale from 1 to 5 according to qualitative parameters as shown in Tab.1.

Tab. 1. Criteria and attributes classification[4].

Classification	Score
Very bad	1
Bad	2
Regular	3
Good	4
Very good	5

The suitability of the study area for the installation of a deep geological repository is measured by combining three main criteria:

- Long-Term Security: refers to security from the geotechnical point of view of the repository, from construction to post-closure isolation.
- Socio-Economic-Environmental Feasibility: concerns the relationship between the construction and operation of the repository and the social and environmental means in the area of implementation.
- Technical Feasibility: it refers to the most important technical criteria in the construction and operation of the repository.

Each criterion consists of a combination of seven attributes, also classified from 1 to 5. The attributes considered were: Lithology, Land Use, and Cover, Hydrogeological Favorability, Mineral Resources, Transport, Slope, and Structures. Fig.1 presents the hierarchical relationship between criteria and attributes.

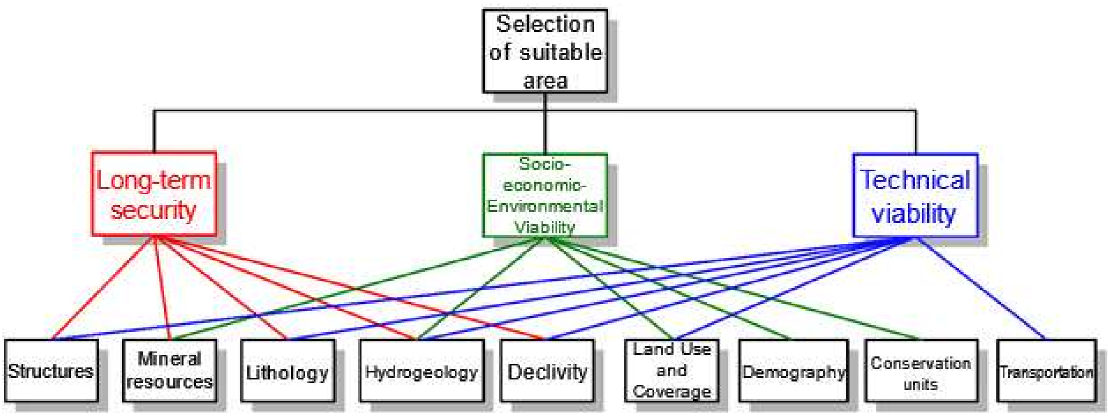

Fig. 1. The hierarchical relationship between criteria and attributes. Adapted from [4]

2.2.1 Attributes

Lithology is one of the main attributes to be analyzed since the geological repository is a permanent underground installation and has the host rock as the last containment barrier. The method chosen for creating the hierarchy of criteria and attributes, the AHP method, involves a qualitative and ordered scale for the standardization and calculation of the values of the assessments involved. In this way, there is a trade-off between the components of each attribute. Therefore, it is not possible, with the method employed, to evaluate different rock classes with the same classification.

This work, as well as that from the reference [4], was based on a geological repository built on hard rocks, such as granites. Such choice comes from the integration between this work and others developed by the authors on the evaluation of the thermal performance of the SF in a repository built-in hard rock. However, it is not possible to exclude other types of rocks in the selection of areas a priori, given that several countries consider other types of rocks for the construction of a geological repository and given the Brazilian geological diversity and its immense territorial extension. For the analysis of the criteria, attributes, and restrictions involved, a geospatial database containing the information specified in Tab. 2 was organized:

Tab. 2. Geodata sources

Attribute	Scale	Source
Lithology	1:500.000	CPRM [7]
Land Use	1:1,000,000	IBGE [10]
Hydrogeological Favorability	1:500.000	CPRM [7]
Mineral Resources	1:100,000	CPRM [15]
Transportation	-	DNIT [9]
Declivity	90 meters	CPRM [8]
Fractures	1:500.000	CPRM [7]

The scores for each attribute were obtained and adapted from Martins [4]. Tab. 3 shows the classification of each attribute.

Tab. 3 Attribute classification. Adapted from [4]

Classification	Lithology	Land Use	Hydrogeological Favorability
1 (Very Bad)	Unconsolidated sediments (clastic and lateritic sediments)	Wet area	-
2 (Bad)	Sedimentary (sandstone, claystone)	Forest vegetation, natural grassland	High
3 (Regular)	Metamorphic (quartzite and shale)	Mosaic of vegetation	Variable
4 (Good)	High Metamorphic (paragneiss)	Agricultural area, pasture, forestry, agricultural mosaic	Low/Very Low
5 (Very Good)	Igneous (basalt, granite)	Uncovered area	No favorability
Classification	**Mineral Resources**	**Transportation**	**Declivity**
1 (Very Bad)	Indicative areas for mineral exploitation	18-30 km	Mountainous
2 (Bad)	-	12 - 18 km	Strongly rugged

3 (Regular)	Areas with potential for mineral exploitation	7 - 12 km	Rugged
4 (Good)	-	3 - 7 km	Gently rugged
5 (Very Good)	Areas without the potential for mineral exploitation	0 - 3 km	Plain

2.3 Weights Assignment

Weights are assigned to each criterion and attribute. The weights of each attribute are the result of the evaluation by specialists in areas of knowledge relevant to the theme requested by Martins [5]. The weight of each criterion corresponds to the geometric mean of the attributes associated with it [4]. Tab.3 presents the weight of each attribute for each criterion and the weight of each criterion in the final evaluation.

Tab. 4 Criteria and Attribute Weights. Adapted from [4]

Attribute	Criterion		
	Long-Term Security	**Socioeconomic and Environmental Viability**	**Technical Feasibility**
Declivity	0.096	-	0.108
Hydrogeological Favorability	0.255	0.154	0.174
Land Use	-	0.432	0.079
Lithology	0.200	-	0.180
Mineral Resources	0.062	0.262	-
Structures	0.321	-	0.301
Transportation	-	-	0.044
Final Weight	**0.578**	**0.224**	**0.110**

2.3 Creation of suitability maps

A GIS software, in this work the ArcMap®, was used for the evaluation of the specialists, through the weights of the attributes/criteria, and the spatial data. Spatial data were obtained from the databases of the following government agencies, CPRM, IBGE, and EMBRAPA. Given the diverse origin of spatial data, the WGS 1984 Geographic Coordinate System was used as a standard and all vector files were converted to raster.

The reclassify tool of the Spatial Analyst extension was used to assign the data, already standardized in raster format, the values of Tab. 2 and Tab. 3. In the specific case of the transport attribute, the Euclidean distance tool of the same extension was used to first, calculate, for each cell, the Euclidean distance to the point closest to the highway axis, and then use the reclassify tool.

The scores of the attributes represented in the layers are represented by a square matrix, $\boldsymbol{M_{ij}}$, of order $\boldsymbol{m}$. The aggregated layer, represented by the criteria, is a square matrix, $\boldsymbol{R_{ij}}$, of order m that can be calculated by a linear combination between the matrices $\boldsymbol{M_{ij}}$ and the weights of each attribute, $\boldsymbol{w_k}$,

$$R_{ij} = \sum_{l=1}^{l} M_{ij}^{l} * w_{k}^{l} \tag{1}$$

where $\boldsymbol{l}$ represents the number of information layers (attributes) used in the analysis of each criterion. Similarly, the final SI of the studied region, $\boldsymbol{A_{ij}}$, is obtained using a linear combination of the $\boldsymbol{R_{ij}}$ matrices and the weights of each criterion.

$$A_{ij} = \sum_{l=1}^{l} R_{ij}^{l} * w_{k}^{l} \tag{2}$$

Where $\boldsymbol{l}$ represents the matrices of criteria obtained by equation 2. The matrix operation in equations 1 and 2 is performed with the aid of the Raster Calculator tool, which yields the suitability index of the state of Espirito Santo for the construction of a geological repository.

3. RESULTS

Fig.2 shows the inadequate and suitable areas for the construction of the repository in Espírito Santo. In none of the analyzed criteria, there were areas considered very good for installing the repository. In the state, there is a predominance of areas considered regular. The areas considered good occur in the northeast part of Espirito Santo. The inadequate areas are the result of the current mineral exploration and environmental protection areas.

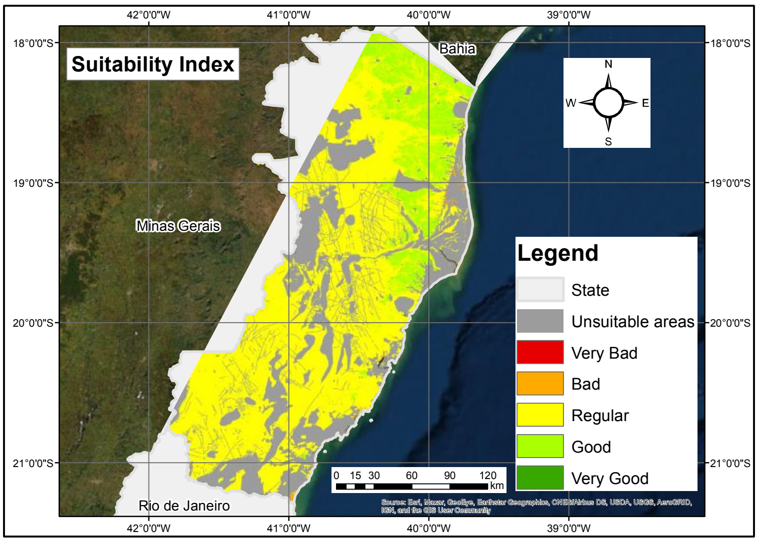

Fig. 2. Map of the Suitability Index of Espírito Santo.

When analyzing, together, the areas of greatest suitability and the areas with the highest classification of the lithology attribute, it is possible to perceive some areas of great interest for future investigations (Fig. 3). In these areas, marked in orange, despite the complex geostructural and geotectonic evolution that the state of Espírito Santo has undergone, a domain of undeformed granitoid complexes is found. Of calm tectonic origin, magmas of different compositions crystallized in granitoids without or with little observed ductile deformation. Such units are well distributed throughout the state [7]. They are regions of interest due to the presence of poor soils that hinder agriculture, areas with low hydrogeological potential, and granites of low commercial interest [7], [16].

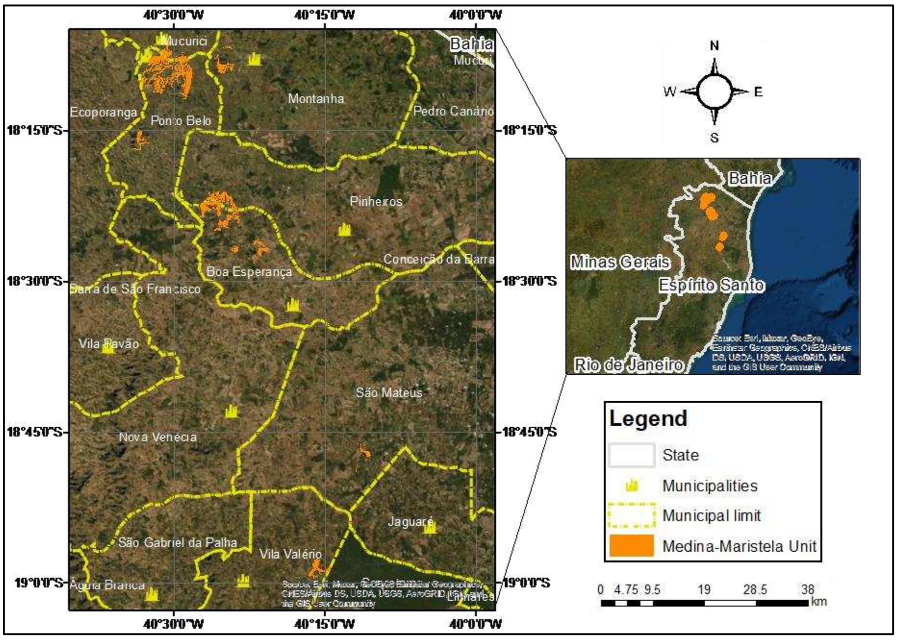

Fig. 3 Detail of areas of interest for further studies in orange.

4. CONCLUSION

Given the great territorial extension of the state, the multicriteria analysis combined with the GIS simplifies the task of selecting areas for further studies of areas suitable for receiving a geological repository. The areas with undeformed granitoid formations, from the Medina-Maristela unit, have the potential for the installation of a Brazilian repository, given their characteristics, and are considered areas of interest for further in-depth studies. These formations are concentrated in the northern part of the state of Espirito Santo. In addition, considering that other types of rock may house a repository, it is important to redo the study considering, possibly, another set of more appropriate attributes for each type of rock.

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