Research Article

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Hypothetical economic valuation of environmental damage (VEDA) using the VERA methodology in the rupture of a uranium mining tailings dam: a case study in Caldas-MG - Brazil

Abstract

Indústrias Nucleares do Brasil (INB), arises from Brazil's growing nuclear activity, aiming to supervise the nuclear fuel cycle. Its installation reflects the Brazilian government's interest in nuclear energy for industrial and technological development. In Caldas INB's presence is linked to uranium exploration whose deactivation in 1995 had an impact on its management of radioactive waste. The tailings dam, classified as High-Risk Category (CRI-Alto) and High Risk Associated Potential Damage (DPA - Alto), stores 2,5 million cubic meters of radioactive material, representing an environmental risk as well as security risk to surrounding communities. In this work, a methodology for delineating floodplains with a 250 – meters influence area was developed based on [6, 26]. The areas of natural vegetation at risk in the event of tailings dam rupture were estimated. Then the methodology of Economic Value of Environmental Resources (VERA) was adopted to perform the Economic Value of Environmental Damage (VEDA), resulting in a significant value of approximately US$290 million dollars. The conclusion was a critical importance of implementing robust prevention and mitigation measures to avoid potential catastrophic consequences involving the collapse of the tailings dam. The results of the present work emphasize the need for the company to focus on preventive actions against the collapse, since the damage to the vegetation of 1 of the dams alone was estimated at approximately 290 million dollars. This value, when added to other values related to environmental damage to water, soil and air, will be much greater than the preventive measure of decommissioning 3 INB dams in Caldas, Minas Gerais.

Keywords: tailings dam, INB in Caldas, georeferencing techniques, flood inundation, economic valuation of environmental damage

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Abbreviations: INB, indústrias nucleares do Brasil; VEDA, economic value of environmental damage; VERA, economic value of environmental resources

Introduction

The Indústrias Nucleares do Brasil (INB) was established in 1988 as a response to the growing nuclear activities in the country and the need for an entity to oversee the nuclear fuel cycle,[1] dating back to the nuclear ventures of the 1960s and 1970s.[2] At that time, Brazil was experiencing a period of intense industrialization, technological development, and a growing interest in nuclear energy,[3] with the government deeming nuclear energy crucial for national progress, both in civilian applications and military installations.[4] Consequently, the National Commission for Nuclear Energy (CNEN) was established, followed by the creation of INB.[2,5]

In the city of Caldas, located in the Southern region of the state of Minas Gerais, the presence of INB is tied to the uranium exploration in the area, known for its deposits of this mineral. During the 1980s and 1990s, the former Minero-Industrial Complex of the Poços de Caldas Plateau (CIPC) operated in the extraction and processing of uranium, activities later absorbed by INB.[6] However, in 1995, the first ore extraction and beneficiation unit to produce uranium concentrate, inaugurated on May 6, 1982, in Caldas, was deactivated after studies demonstrated the economic infeasibility of continuing activities in the region.[2]

At INB of Caldas, there are 3 dam structures. One of uranium mining tailings, which is the one studied in this work, and two more of uranium mining sediments: D4 and the Nestor Figueiredo Basin - BNF. The tailings and D4 are classified in the SIGBM as a High Risk Category (CRI- High) and High Associated Potential Damage (DPA-High).[7] The BNF is classified as CRI - Medium and DPA - Medium CRI- Medium and DPA - Medium respectively.[7]

In 2019, when the Federal Public Ministry (MPF) requested from INB the presentation of an Emergency Action Plan for Dams (PAEB), due to an unusual event that occurred in September 2018 with the tailings containment structure, it was found after an audit that the system was severely compromised by infiltrations and there was an imminent risk of rupture.[8] Already in 2022, with the promulgation of Law number 14.514/2022,[9] the National Mining Agency assumed responsibility for the oversight of INB's tailings dam and other dam unit in Caldas, previously under the supervision of the National Commission for Nuclear Energy (CNEM).[2] In June 2023, the tailings dam unit was officially classified as a dam in the Integrated System for the Management of Mining Dams (SIGBM), a decision supported by the guidelines of the National Policy for Dam Safety (PNSB),[2] due to its structure being designed for the storage and containment of large volumes of mining waste and being located near a permanent watercourse.[10]

Furthermore, the tailings dam underwent other characteristic inspection procedures to assess the stability of these structures, being classified as High Risk (CRI- High) and with High Associated Potential Damage (DPA- High), lacking a Downstream Containment Structure (ECJ) published in SIGBM, and facing structural problems that increase the risk of rupture.[11]

Information about DPA-High and CRI-High of the tailings dam is also present in the National Dam Information System.[11] Consequently, the current structure is in the process of decommissioning i.e., dismantling and procedures for not characterization, which, according to INB, will be informed in the future in a Decommissioning Plan for the dam.[11]

Regarding the volume of waste, the tailings dam stores approximately 2.5 million cubic meters of radioactive material therefore representing an environmental and public health risk [7]. The construction method of the tailings dam is a single-stage process, meaning that all construction phases are carried out at once, without subdivisions into different stages as in upstream and downstream methods.[7] However, even with this construction model, there is still the potential risk of collapse.

Uranium mining, the main material stored in the tailings dam, is a metallic and radioactive element represented by the symbol "U" on the periodic table and is the mineral component present in uraninite.[12–15] Its radioactive activity makes it valuable for applications in nuclear energy and the manufacturing of nuclear weapons.[2] However, in Caldas, as it is present in mining waste, it is poorly concentrated and has low economic viability for applications in the aforementioned activities, making it unsuitable for use in industrial and technological processes related to nuclear energy.[16] Additionally, it is important to highlight that Brazil is a signatory to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) created in 19 by the United Nations, aiming to prevent the spread of nuclear weapons and promote nuclear disarmament.[17] Therefore, possible destinations for the uranium waste present in the tailings dam in Caldas would be storage in final disposal facilities for radioactive waste, treatment to reduce radioactivity, and, if possible, recycling for future use in compatible industrial or technological processes.[18–25] In the meantime, it is stored, along with other radioactive elements such as thorium and radionuclides like radon,[26] in the tailings dam in Caldas.

According to information recorded in the SIGBM, the eventual occurrence of a disaster involving the tailings dam would result in a environmental impact classified as Very Significant Aggravated, due to the storage of solid waste categorized in Class I,[27] due to the presence of uranium radioactive waste and its by-products.[7]

According to,[26] through the flood map created by the aforementioned authors, it was possible to estimate that the extent of the areas affected by mud and released materials will extend 19 km downstream and affect an area of 2,82 km².[26] The socio-economic impact will be low, as there is small concentration of residential, agricultural, and industrial facilities or infrastructure in the affected area downstream of the dam.[7] However, this does not mean that the socioeconomic impacts can be neglected, as even with a low concentration of infrastructure in the affected area downstream of the dam, the occurrence of the disaster could lead to significant damage in terms of disruptions to local economic activities, loss of natural resources, impacts on public health, and costs associated with mitigation and environmental recovery.

Therefore, considering the potential environmental and socioeconomic impacts of the breach of dam tailings in Caldas, which includes radioactive contamination of water,[28] soil, vegetation, risks to the human security of local and regional communities, as well as risks and instabilities in national security, preventive and security measures are urgently needed to avoid the collapse of the structure.

According to[29] cited by,[30] modeling dam breaches is an active field of research, both theoretical and applied, and of great interest to hydraulic engineers, as floods induced by the breach of dam bring potentially catastrophic consequences downstream.

Therefore, regarding the quantification of the financial and environmental impacts resulting from dam disaster scenarios, some tolls become fundamental. One of these widely used tools for assessing the areas potentially affected by dam breaches is Remotely Piloted Aircraft (RPA's), also known as drones.[31] These tolls are remote sensing platforms capable of capturing images at various altitudes and thus providing more comprehensive information about the area that will potentially be affected or has already been affected.[31] Another tool is the study of Digital Terrain Models (DTMs), with different spatial resolutions, to simulate and evaluate different scenarios of dam breaches.[32] In this sense, the study of floodplains is another instrument that incorporates analyses of the for mentioned tools, and which, according to,[33–37, 8,39,40] refers to the area that will potentially be affected by floods if the dam rupture or water or mining tailings overflow. This area is delimited by the maximum reach that tailings or water from the dam can reach in case of structural failure or extreme event that exceeds the dam's drainage capacity.[32]

Aligned with flood mapping, the Economic Valuation of Environmental Damages, here represented by the acronym VEDA, can be utilized for cases involving dam catastrophes. Developed within the scope of Environmental Economics,[41] it assigns monetary values to environmental damages, facilitating the economic analysis of such losses.[42–45]

However, VEDA faces challenges in evaluating intangible aspects of the environment,[43] requiring complementary approaches for a consistent assessment of environmental damage.[46,47] In the regards, the Economic Value of Environmental Damages (VEDA), is a methodology based on principles of environmental economics and economic valuation of ecosystems,[48–51] allowing for the quantification of economic benefits provided by ecosystems,[52] and serves as a tool to assist component authorities, such as environmental experts, analysts, prosecutors, judges and the like in decision-making in relation to environmental pecuniary compensation for human actions that generate environmental damage.

The methodology in question can employ different methods to quantify its variables, such as Direct Use Value (VUD), Indirect Use Value (VUI), Option Value (VO), and Existence Value (VE).[41,48,49] For this purpose, methods such as Replacement Costs, Opportunity Costs, Avoided Costs, Control Costs, among others, can be used to achieve the value of VEDA.[42,51,53,54]

This study evaluated the flood mapping resulting from the hypothetical breach of the tailings dam in Caldas, created by[6] and,[26] remodeled in this work, and through the remodeled flood mapping, aimed to understand the amount of native vegetation that will be lost in event of dam failure. Subsequently, VEDA was conducted to estimate the value of the damage represented by the decrease in biome vegetation, changes in the natural landscape, etc., resulting from the catastrophic event. Thus, essential information will be provided for the environmental management of the dam, for decision-making by INB in Caldas and government agencies, related to dam safety, as well as the conservation of plant biodiversity in the area. This research is aligned with the UN Sustainable Development Goals (SDGs),[55] especially SDG 15 – Life and Land, by addressing issues related to the conservation of biodiversity and terrestrial ecosystems.[55] Furthermore, it is related to SDG 13- Climate Action,[55] by considering the potential environmental impacts of a catastrophic event, such as the breach of the tailings dam in Caldas and its consequences for the environment.

Characterization of the study area

The tailings dam of INB, also known as the Decommissioning Unit of Caldas (UDC), is located in the city of Caldas, approximately 30,9 km from Poços de Caldas, both in the southern region of the state of Minas Gerais,[2] and 462,2 km from the capital, Belo Horizonte.[56] The mentioned dam comprises an area of 13,6km² store waste from uranium mining, including thorium waste,[20] therefore materials with potential radioactivity, albeit in lower concentrations. The biome present is the Atlantic Forest, considered a Tropical Forest, and is one of the main plant formations in Brazil[57] internationally recognized as a biodiversity hotspot,[23,58] harboring a wide range of endemic species and also those threatened with extinction.[59,60] Its destruction would result in irreparable loss of biodiversity compromising the stability of local and regional ecosystems.[61–63]

According to,[65] the UTM of Caldas, currently the UDC under study, is located at the source of three rivers, namely Ribeirão das Antas, Ribeirão do Soberbo, and Córrego da Consulta. Such perennial watercourses[64] play an important environmental and hydrological role in the region[65] and perform a fundamental role in the balance of local ecosystems, serving as habitat for various species of fauna and flora.[56] However, all this potential is threatened by the potential breach of the tailings dam, which stores mining waste from radioactive elements. Regarding soils, Caldas has a predominance of Red and Yellow Latosols, associated with areas of high relief, and Argisols in flatter terrain,[66] which directly influences agricultural practices and the conservation of natural resources in the region.[56]

According to research conducted by IDE-Sisema, the vegetation near the tailings dam is characterized by remnants of Atlantic Forest in areas of higher relief and Cerrado vegetation in flat terrain.[66] Therefore, it is evident that the collapse of the dam structure would pose a serious threat to this natural capital, compromising not only biological diversity but also the ecosystem services provided by them, benefiting both nature and the local and regional community. In Figure 1 below, we have the image from Google Earth Professional referring to the dam under study.

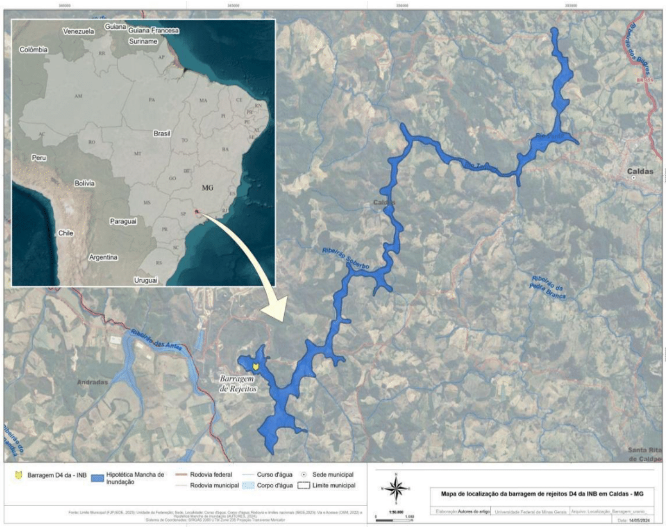

Figure 1 Location map of the uranium dam in Caldas, Minas Gerais, with floodplain zone.

Materials and methods

Based on the data information contained in the flood footprint developed by,[6] a new map was created delineating an expanded flood are, according by an influence area, i.e., an area surrounding the flood area within 250 meters, aiming in this specific case of dams, to mitigate the influence and expansion of the flood footprint, resulting in the effective study area. This supplementary influence zone aims to mitigate environmental impacts arising from flooding, as well as predict environmental damages within this delineation with a margin of safety. Within the effective study area, a land use and land cover map was developed by compiling the 2022 collection from,[67] using ArcGis, 10.8 software for reclassification and obtaining quantifications of each class. In this same process, existing databases in the Integrated Mining Dam Management System (SIGBM)[7] were also utilized. In anticipation of the imminent loss of natural vegetation within the effective study area due to the hypothetical breach of the tailings containment structure, the scientific approach manifested in this work involved conducting the Economic Valuation of Environmental Damages (VERA). This methodology employed economic-financial calculation, anchored in the concepts of the Economic Value of Environmental Resources (VERA). These principles are outlined in Decree nº.4.339, dated August 22, 2002, referring to the Brazilian National Biodiversity Policy,[68] and are also supported by the Brazilian Association of Technical Standards (ABNT), by standard NBR 14.653/2008 and updated in 2009.[69] Additionally, the VERA methodology is endorsed by Ordinance 118, dated October 3, 2022, issued by the Brazilian Institute of Environmental and Renewable Natural Resources (IBAMA).[70] This ordinance establishes the Standard Operational Procedure (POP), aimed at estimating the implementation costs of environmental restoration projects in Brazilian biomes, to compose the mining value of compensation for environmental damages to native vegetation, in administrative procedures within IBAMA.[70] VERA was estimated firstly by summing indirect costs using the Value of Indirect Use (VUI), Option Value (VO), and Existence Value (VE). To estimate the VUI, VO, and VE values, updated values for the exchange rate of the dollar as of June 19, 2024, in Brazil, were employed, referring to the ecosystem services of the Tropical Forest and Grass/Rangelands cited by.[71–75] Considering that the Atlantic Forest biome shares characteristics of the Tropical Forest and the Cerrado biome shares characteristics of the grass/rangelands biome, in this work adaptations were to estimate ecosystem services. We will therefore consider the Atlantic Forest biome as the Tropical Forest and the Cerrado biome as the Grass/Rangelands biome to calculate ecosystem services. It's worth mentioning that in this work we are exclusively studying natural vegetation. Therefore, we focus our values on hectares of vegetation in forest formations, grassland formations and savannah formations, as shown on the map in figure number 4. In figure number 4, we have the number of hectares of separate pastures, but we will not use their value, as they are not exclusively natural pastures.

The sum of VUI+VO+VE represents the total ecosystem services provided by vegetation in the area, therefore being indirect costs. To estimate lost profits, i.e., the period during which the area will be exposed to degradation effects and irreversibility of damages, a time horizon of 25 years was used, which according to,[76–78] reflects a generational cycle and according to[76] as cited,[78] refers to the average forest rotation period.

However, we must take into account that if the dam collapses and the area becomes contaminated with radioactive uranium waste, including its decay by-products, it is possible that this area will need hundreds or, in a more pessimistic projection, thousands of years to be recovered. In this sense, 25 years represents in this work only a time horizon for valuing damage to vegetation so that such values can be used for the purposes of environmental pecuniary compensation for the vegetation cover by the competent authorities and public institutions responsible for valuing damages.

Thus, to calculate the value of ecosystem services that will be lost in the area, which will be subject to degradation effects for at least 25 years, the ecosystem services of the area, transformed into hectares, were multiplied by the lost profits.

There is no prohibition in the global legal system and in environmental economics, for the use of three different methods to value the Value of Direct and Indirect Use, when it comes to the methodology of the Economic Value of Environmental Resources. It is possible to calculate values related to costs for environmental recovery, costs related to land value and costs related to cleaning and removal of tailings sludge in a single method, such as by Replacement Cost Method (MCR). However, in this work, we chose to value each of the variables mentioned in 3 different methods, each containing its own justification for use.

Direct costs were estimated using the Replacement Cost Method (MCR), Opportunity Cost Method (MCO), and Avoided Costs Method (MCE). MCR refers to the costs necessary for the replacement of the lost asset or resources.[79] In this sense, as it concerns the valuation of damages to vegetation, environmental recovery techniques from vegetation present in Ordinance nº 118, dated October 3, 2022 of[70] were used. These techniques are divided by biomes. For the Atlantic Forest biome, the techniques are: Nucleation at US$ 4,459.083/ha; Seeding planting, including nucleation at US$ 3.556.49/ha; Seedling planting, excluding nucleation at U$$ 3,255,63/ha, and Natural regeneration management at US$279,083/ha.[70] The sum of these values for recovery, considering the Atlantic Forest biome, totaled U$$11,550.29/ha. Considering that this work also took into account potential losses of vegetation typical of the Cerrado biome, such as savanna and grassland formations, environmental recovery techniques present in[70] for the Cerrado biome were: Seedling planting (savanna formation) at US$2,771.74/ha; Direct sowing (savanna formation) at US$2,960.092/ha; Natural regeneration management (savanna formation) at US$ 3,293.302/ha; Direct seeding (savannah formations) US$2,855.23; Driving natural regeneration (forest formations) US$ 533.027; driving natural regeneration(savannah formations) US$290.00. The sum of these techniques resulted in US$ 12.703,4/ha. By summing the necessary recovery techniques for the Atlantic Forest vegetation with the sum of the necessary recovery techniques for Cerrado vegetation, the value of US$24,253,68.00 3/ha was obtained. In obtaining the MCR value, the total value of the two necessary recovery techniques for the replacement of vegetation was multiplied by the total number of the hectares of natural vegetation within the flood footprint and influence area (grassland formation, forest formation, and savanna formation), approximately 715.89 hectares.

The Opportunity Cost Method can be applied, arguing that the company chose to sacrifice the benefits of avoiding the disaster by choosing other alternatives,[80] which may result in extremely negative future losses. This is because if the Brazilian Nuclear Industries, in Caldas, do not take preventive action or invest in security measures in time to prevent a possible dam disaster, then they may be choosing to save costs in the short term, but these would result in very high and significant costs in the long term, which may include loss of human, animal, and plant lives, environmental and economic damages, as well as damages to the company's image, reputation, and credibility. If the company opts for the worst-case scenario, it will be missing the opportunity to take preventive mitigating measures on the dam, perhaps prioritizing other considerations, such as short-term cost maximization. Thus, MCO was calculated based on the Value of Unimproved Land (VTN),[81] for the city of Caldas, which according to the company is US$ 1.702,54. We considered VTN for calculating MCO, arguing that the area potentially affected by the collapse of the tailings containment structure will lose its function of preserving flora or fauna, as stated in,[81] thereby losing the opportunity to preserve it. Then, VTN was multiplied by the total number of hectares of natural vegetation (grassland formation, forest formation, and savanna formation), which will be lost in case of dam collapse approximately 715.89 hectares.

Taking preventive and mitigating measures to prevent the breach can reduce costs, eliminating the need for cleaning the collapse area, expenses on machinery and workers for sediment and mud removal, compensation payments to families for loss of human lives, among others. Thus, in this work, MCE was carried out by estimating the costs necessary for cleaning the affected area, costs of equipment necessary for the work (dredges, slurry pumps, hydraulic excavators, dump trucks)[82] number of workers required for area cleaning in 1 year, total hours of work required for area cleaning in one year, and estimation of market prices for specific Personal Protective Equipment (PPE) for workers, due to the potential radioactive waste. Cleaning and removing uranium tailings sludge and its byproducts from the area may be technically impossible. However, for the purposes of environmental pecuniary compensation from the company to the state, financial estimates and calculations must be presented by the competent authorities in charging environmental liability, such as the Public Prosecutor's Office and the Judiciary.

It is emphasized, therefore, that MCO and MCE, despite being direct costs, can be considered variable costs, as VTN may be higher depending on which year the dam will breach, if it does. MCE, on the other hand, will depend on the magnitude of the disaster in practice, which may be very different from that projected in this work, thus requiring additional costs.

At the end of the calculations, a comparative analysis was conducted between the projected total VEDA value and the control cost, which would be the costs related to disaster prevention. This comparison allows evaluating the costs involved in the pecuniary compensation owed by the company to the state in contrast to the costs necessary for the implementation of mitigation measures before the disaster occurs.

Practical development

Flood zone buffered for 250 meters

This study developed a map contain a flood zone based on the studies of the flood zone created by[6] and,[26] for tailings, as shown in Figure 2 below.

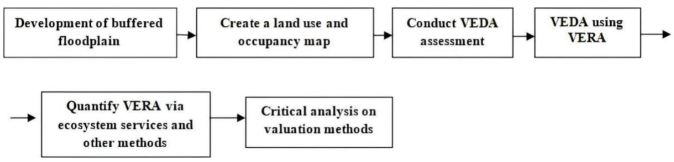

Figure 2 General methodology for research development. Produced by the authors.

Within the delineated flood zone for this study, a 250-meter buffer was established, as outlined in the Materials and Methods section.

Analysis of the land use and occupation map revealed the presence of the following types of natural vegetation, excluding flooded fields and marshy areas within the flood buffer zone: 89,115.113 hectares of Grassland Formation, 374,669.211 hectares of Forest Formation and 252,097.184 hectares of Savannah Formation. The quantities of hectares of natural vegetation at risk of loss serve as the focal point of our inquiry. This outcome is depicted in Figure 3 below.

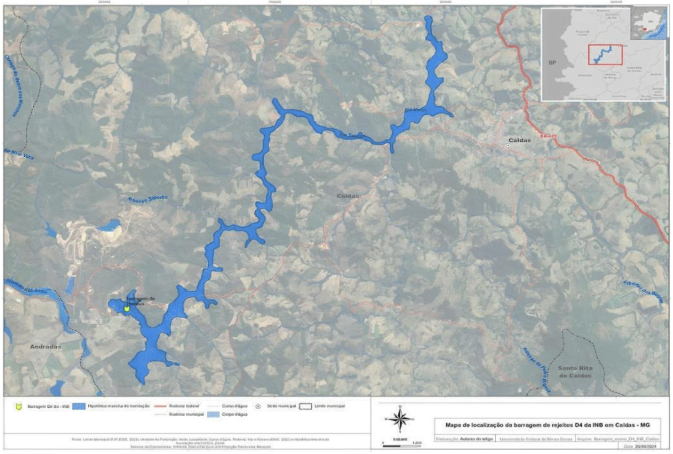

Figure 3 Floodplain map. Produced by the authors through the[6] and.

Excluded from this study were planted vegetation such as pasture and agricultural areas. This choice is justified by the decision to focus on the impacts of tailings breach specifically on natural vegetation present in the flooded area. This approach allows for a more precise and direct analysis of the environmental damages caused by the potential event, avoiding the introduction of variables that may contradict the study's objective. Additionally, by concentrating solely on variables related to natural vegetation, we can better understand the long-term implications for local ecosystems and formulate more effective strategies for environmental mitigation and conversation (Figure 4).

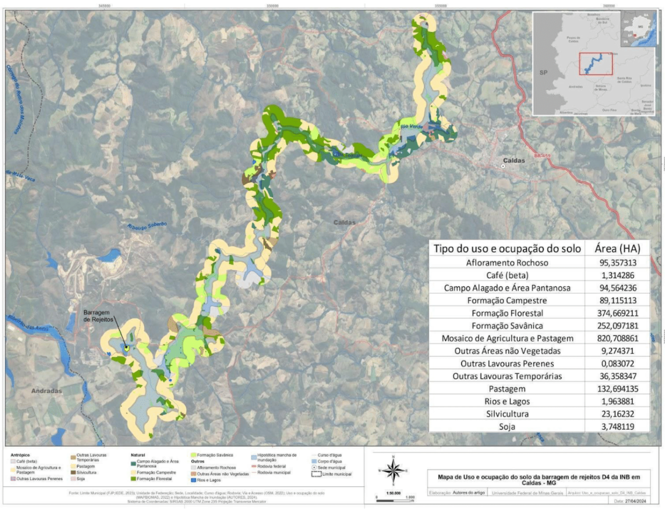

Figure 4 Floodplain land use and occupancy map. By the authors. [26]

Another argument for not studying planted areas in this research is that these areas may be restored or replaced by humans after the flooding event, depending on the degree of contamination. In contrast, the recovery of natural ecosystems may be a slower and more complex process, with long-term implications for biodiversity and local ecosystem services.

Economic Valuation of Environmental Damages (VEDA) calculations

The methodology of Economic Value of Environmental Resources (VERA) involves assigning economic values to the following variables[41]:

VERA = VD + VUI + VO + VE

In this context, the afore mentioned variables signify:

VERA = Value of Environmental Resources;

VD = Direct Use Value.

This value is associated with the direct consumption of a resource.[41] Specifically, regarding dam breaches, VD represents the direct costs associated with the loss, repair, such as vegetation, soil, water, etc;

VUI = Indirect Use Value. This value is related to the benefits derived, for example, from ecosystem services and functions[41];

VO = Option Value. When related to ecosystem functions and services, VO refers to the assignment of values in direct and indirect uses that may be captured in the future and whose preservation may currently be threatened[41];

VE = Existence Value. When related to ecosystem functions and services, it is the value of the existence of such goods and is related to the moral, altruistic, and cultural position regarding the rights of existence and preservation of natural resources.[41]

To capture the value of VUI+VO+VE, we adapted the tables of ecosystem services value from authors[71–75] for Tropical Forest Grass/Rangelands biomes. The adjustment of values was made by updating the tables, correcting dollar inflation by the United States of America CPI of US$ 1.4 index and considering the exchange rate of US$1 equal to R$ 5.45, on June 19, 2024. From the above, the results were as follows in Table 1 and Table 2.

Table 1 Ecosystem services adapted from[71–73,75] for Tropical forest biomes, representing the Atlantic forest

Ecosystem services	U$$ ha/year	Conversion of R$ (exchange rate R$ 5.45)
Gas regulation	16.8	91.56
Climate regulation	2,861.60	15,595.72
Disturbance regulation	92.4	503.58
Water regulation	11.2	61.04
Water supply	37.8	206.01
Erosion control	471.8	2,571.31
Soil formation	19.6	106.82
Nutrient recycle	4.2	22.89
Waste treatment	168	915.6
Pollination	42	228.9
Biological Control	15.4	83.93
Habitat/refuge	54.6	297.57
Food Production	280	1,526
Raw Materials	117.6	640.92
Genetic Resources	2,123,8	11,574.71
Recreation	1,213.80	6,615.21
Cultural	2.8	15.26
Option value	2.8 74	15.26
Existence value	4.2 74	22.89
Total	7,540.40	41,095.18

Table 2 Ecosystem services adapted from[71,74,75] for Grass/Rangelands biomes, representing the Cerrado

Ecosystem services	U$$ ha/year	Conversion of R$ (exchange rate R$ 5.45)
Gas regulation	12.6	68.67
Climate regulation	56	305.2
Water regulation	4.2	22.89
Water supply	84	457.8
Erosion control	61.6	335.72
Soil formation	2.8	15.26
Nutrien recycle	251.1675	1,368.82
Waste treatment	105	572.25
Pollination	49	267.05
Biological control	43.4	236.53
Habitat/refuge	1,699.60	9,262.82
Food Production	1,668.80	9,094.96
Raw Materials	75.6	408.75
Genetic Resources	1,699.60	9,262.82
Recreation	36.4	198.38
Cultural	233.8	1,274.21
Total	6,083.56	33,155.40

The exchange rate for 1 US dollar, quoted on 19/06/2024, at 1:20 pm Brasília time, was R$5.45 (five reais and forty-five cents), according to Google Finance. Adding the ecosystem services in tables 1 and 2, relating to the Atlantic Forest and Cerrado biomes represented by the values of Tropical Forest and Grass/Rangelands respectively, in reais/ha/year, we arrive at the value of R$74,250.58/ha/year. Multiplying the ecosystem services in hectares per year by the number of hectares of natural vegetation that will be lost in the event of a dam failure, we arrive at R$74,250.58/ha/year x 715.89 ha = R$53,155,247.72/year. This value in dollars means US$9,753,256.46/year.

To capture the lost profits i.e., the value for the period during which the area will be exposed to degradation effects, considering 25 years, we do the following: R$53,155,247.72/year x 25 year = R$1,328,881,193.00 or US$243,831,411.60.

To capture of all variables presented in the VERA concept, we now need to estimate the VUD. The VUD will be estimated in this work through the MCR, MCO, and MCE. For the MCR, the value of the sum recovery techniques for both the Atlantic Forest and Cerrado biomes, as present in Ordinance nº 118 of IBAMA, is US$ 24,253.68. Multiplying the value by 715.89 hectares, we have US$17,362,964.87. This is the value of the MCR.

To calculate the MCO, we use the Value of Unimproved Land,[81] US$ 1,594.66 dollars for the preservation of flora or fauna in the city of Caldas/MG.[81] And we multiply the VTN of Caldas by the number of hectares of natural vegetation within the buffered floodplain, which is 715.89 hectares. This result is US$ 1,141,601.54.

The MCE is calculated in this work based on the necessary costs for machinery, workers, working hours, Personal Protective Equipment, et., and was carried out as follows:

Total hours worked in 1 year, considering full-time hours of 40 hours, in Brazil, per week for each worker: 8 hours x 365 days/year = 2,920 hours/year.

To calculate the estimated operational costs in 1 year, we use the price table of SUDECAP/PBH,[82] which contains prices of machines and equipment necessary for cleaning the area.

a) Sludge pumps = R$11.14/hour[82] x 2,920 hours x 15 units = R$487,932.00 or US$89,528.81;

b) Dredgers: R221.30/hour[82] x 2,920 hours x 15 units = R$9,692,940.00 or US$1,778,521.101;

c) Hydraulic excavators: R$221.30 hours[82] X 2,920 hours x 10 units = R$6,461,960.00 or US$1,185,680.74;

d) Dump trucks: R$175.74/hour x 2,920 x 30 = R$15,394,824.00 or US$2,824,738.35.

e) Total labor costs in 1 year:

f) Total hours worked per year: 2,920 x 250 workers = 730,000 (seven hundred thirty thousand hours);

g) Total labor costs: 730,000 hours x R$150.00/day = R$109,500,000.00 or US$20,091,743.12;

h) Costs with Individual Protection Equipment for workers, considering: Chemical protection suits, as it is a potentially radioactive waste dam, with an estimated market price of R$350.00 each or US$64.22;

i) Gloves and productive boots. We will use an estimated of R$100.00 each or US$18.35;

j) Respiratory masks: R$100.00 each or US$18.35;

k) Protective goggles, R$50.00 each or U$9.18;

l) Helmets R$ 100.00 each or US$18.35;

Market research with average assessment of PPE values at the following stores[83,84] considering minimum price The sum of these values per person is: R$700.00 (US$128.45), the unit price of PPE.

Considering that there will be 250 workers R$700 x 250 = R$175,000.00 (US$32,110.09). Thus, the total operating costs:

US$89,528.81 (sludge pumps) + US$1,778,521.101 (dredgers) + US$1,185,680.74 (hydraulic excavators) + US$2,824,738.35 (dump trucks) + US$20,091,743.12 (labor costs in 1 year to clean the area) + US$32,110.09 (PPE) = US$ 26,002,322.21. This is the MCE value.

Therefore, the Economic Valuation of Environmental Damages caused by the hypothetical rupture of the tailings dam in Caldas would cost the responsible company the environmental compensation for the damages caused, solely for the quantify of hectares of natural vegetation lost, the amount of:

Total VEDA = [(VUI+VO+VE) x Lost profit] +MCR+MCO+MCE = Total VEDA = US$243,831,411.60 + US$17,362,964.87 + US$ 1,141,601.54 + US$ 26,002,322.21 = US$288,338,300,2 (approximately US$290 million dollars. This value in Brazilian reais represents R$1,571,443,736.00.

Discussion

The direct economic impacts associated with a potential collapse would be considerable and multilateral. They would encompass revenue losses from both the company responsible for the dam and the Brazilian state, which would be required to allocate efforts and personnel to work on necessary response and mitigation operations.

Additionally, with the rupture there would be municipal revenue losses due to possible disruptions of local economic activities and damage to the company's and Brazil's reputation on the international stage. The mentioned direct impacts would be amplified by indirect effects that have the potential to be even more far-reaching. This may include the irreparable loss of biodiversity within the Atlantic Forest biome and other existing vegetation within the area belonging to other biomes, as well as damage to the social economic well-being of local and regional populations, thus contributing to a state of general insecurity.

Therefore, the analysis found in this work, based on scientific and economic data, emphasizes the urgency of coordinated and effective actions to prevent dam failure and protect both the environmental and potentially affected communities.

The implementation of preventive and mitigating measures would not only reduce the risks of environmental and economic damage but would also safeguard the natural resources present in the studied region. It is important to note that this analysis represents a projection based on a hypothetical scenario of potential damages associated with the failure of the dam in question and, therefore, it is essential, and therefore, it is essential to recognize that in the event of a real disaster, the damages could be substantially more significant and unpredictable than estimated in this study. Therefore, it is emphasized that the VEDA of this work is only valid for estimating environmental damage to vegetation in the area, in order to assist the judicial seconds in decision-making.

Regarding the methods used based on the VERA methodology, it is worth mentioning that both MCR, MCO, and MCE can be considered direct costs, but they are variable costs in the specific case under study. MCR is variable because if the dam ruptures and damages much larger quantities of hectares of vegetation than estimated in this work, then more environmental recovery techniques and more species of vegetation to be planted or down, etc. would be necessary. The VTN/EMATER of MCO may vary over the years if the land is valued for the preservation of flora or fauna, as happened with the city of Nova Lima, according to the VTN/EMATER of the year 2024.[81] The MCE estimated in this work is underestimated due to the lack of budget for other machines, equipment, techniques, etc., necessary for cleaning the area due to the spillage of uranium mining waste and other potential radioactive elements in the soil. Regarding VUI+VO+VE, these depend on the dollar value at the time of dam rupture. If the dollar is higher, then the values of ecosystem services multiplied by the lost profit should be higher, and vice versa. It is also emphasized that this work studies only the damages resulting from the hypothetical rupture in natural vegetation. Damage to the soil, damages to watercourses, and damages to the air were not studied.

Another relevant factor in this analysis is the complexity of natural systems and the interactions existing within the 250 –meter buffered floodplain, which makes it difficult to predict with absolute certainty the exact unfolding of the catastrophic event. Therefore, it is of utmost importance to approach this analysis with an understanding of its limitations and recognize the continuous need for research in the area of dams, especially those involving mining waste and potentially radioactive waste, in order to better manage the risks associated with rupture events.

The final analysis of this work is based on control costs associated with the costs for prevention and mitigation of rupture. Such costs are difficult to estimate in the case of the dam under study, as the dam stores materials with radioactive potential, and therefore, the company may have classified and confidential information regarding the state of conservation and repair needs of the dam. However, considering the decommissioning of dams as a preventive measure against failure and knowing that the costs for the decommissioning of INB dams in Caldas will be around 500 million dollars,[85,86] the results of the present work emphasize the need for the company to focus in preventive actions against the collapse, since the damage to the vegetation of 1 of the dams alone was estimated at approximately 290 million dollars. In other words, the company's financial losses could be inestimable if the dam collapse occurs, as well as the environmental damage, which could make the area unviable for any purposes or even for life for many years.

Conclusion

The Economic Valuation of Environmental Damage (VEDA), valued at more than 1 billion reais in Brazil or approximately US$290 million dollars, reflects the magnitude of environmental damage that could occur in an extensive area of 715.89 hectares, covering the 250-meter buffered floodplain, specifically focusing on the studied natural vegetation. The significance of this value is unequivocally relevant and emphasizes the need to implement efficient prevention and mitigation measures to avoid the catastrophic scenario.

The study of the flooded area, combined with the VERA, can support research on disaster management involving nuclear waste in Brazil and worldwide, as well as the challenges of biodiversity conservation in these locations. Additionally, it helps to understand the value of the affected ecosystems.

Based on the analyses of the calculations of the Economic Valuation of Environmental damage (VEDA), employing the concepts of the Value of Environmental Resources (VERA) methodology, the unequivocal need for a comprehensive analysis to evaluate potential outcomes is emphasized, considering the hypothetical rupture tailings dam, in Caldas. In addition to considering the economic costs of the disaster to the environment, it is important to know other possible impacts on other spheres of society.

The evaluation presented on the ecosystem services provided by the vegetation that will be lost in the event of rupture provides a project view of the imminent damages that can affect not only the economy but also the well-being and health of local and regional populations. The potential environmental damages represent a serious threat to the ecological integrity of the region, with the potential to trigger irreparable losses of habitats and ecosystems existing in the Atlantic Forest biome of the region.

The value found in VEDA, for possible damage to vegetation, calculated in this work, could be used as a form of environmental insurance by the company to assist in procedures for preventing and mitigation environmental damage, specifically for vegetation. There are environmental insurance companies in parts of the world that work with policies related to the prevention and mitigation of environmental damage. In this way, the company would preserve its socio-environmental image and avoid environmental damage that, in practice, could be much greater than those mentioned in this work, when specifically dealing with damage to hectares of vegetation. In this work, the highest VEDA was demonstrated when ecosystem services were estimated.

The general results of the present work emphasize the need for the company to focus on preventive actions against the collapse, since the damage to the vegetation of 1 of the dams alone was estimated at approximately 290 million dollars. This value, when added to other values related to environmental damage to water, soil and air, will be much greater than the preventive measure of decommissioning 3 INB dams in Caldas, Minas Gerais.

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Conflicts of interest

There is no conflict of interest.

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