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Research paper

Analysis of land use change after the Brumadinho tragedy and its legal implications

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ABSTRACT: On January 25, 2019, the "Barragem I" in Brumadinho, state of Minas Gerais, caused significant socio-environmental damage when it burst. 665 victims were identified, with 270 deaths, and unprecedented environmental impacts in the watershed. In this study, we assess land use and land cover changes following the dam damage and the legal implications of these changes. The results show that the tailings extended over 306.95 hectares, burying approximately 98 buildings. Of this area, 45.9% was occupied by native vegetation, 22.19% by agricultural activities, and 2.5% by urban areas. The event caused irreversible impacts on the water quality of the Paraopeba River, decimating ecosystems, leading to socioeconomic destabilization of the region and violating legal environmental requirements. Principles and laws clarify that the principle of prevention, human dignity, and the laws of the National Policy on Dam Safety, the Federal Constitution, and the National Environmental Policy were violated.

Keywords: dam, geoprocessing, mapping, legislation.

RESUMO: No dia 25 de janeiro de 2019 a Barragem I em Brumadinho, Minas Gerais, causou grande prejuízo socioambiental ao se romper. Foram identificadas 665 vítimas, com óbito de 270 pessoas, e impactos ambientais na bacia sem precedentes. Neste estudo foi avaliada a mudança de uso do solo após o rompimento da barragem e a implicação legal dessas alterações. Os resultados mostram que o rejeito se estendeu por 306,95 hectares, e cerca de 98 edificações foram soterradas. Desta área, 45,9% eram ocupados por vegetação nativa, 22,19% por atividades agrícolas, e 2,5% por área urbana. O evento gerou impactos irreversíveis na qualidade da água do Rio Paraopeba, dizimou ecossistemas, levou à desestabilização socioeconômica da região e violou requisitos ambientais legais. Princípios e leis levantados esclarecem que o princípio da prevenção, da dignidade humana e leis como a Política Nacional de Segurança de Barragens, Constituição Federal e Política Nacional do Meio Ambiente, entre outros, foram violados.

Palavras-chave: barragem, geoprocessamento, mapeamento, legislação.

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INTRODUCTION

The state of Minas Gerais holds significant importance for the Brazilian mining industry, particularly in the production of major metallic substances. Notably, the state accounted for 69.5% of national iron production, 96.6% of zinc production, and 12.9% of niobium production (ANM, 2018). However, this activity leads to irreversible environmental impacts, including water and air pollution, noise and visual pollution, and considerable changes in land use. These changes can affect various economic activities, such as agriculture and the provision of ecosystem services.

Concerns about the environmental impacts of mining have increased following recent dam failures in Brazil. There are 614 dams in the country primarily used for containing mining tailings, 23.12% of which are situated in the state of Minas Gerais, and 64% of these dams have a high potential for associated damage in the event of failure (ANA, 2024). The emergence of tailings dams was driven by mining activities aiming to sustain ore extraction and mitigate the environmental impacts associated with this activity. However, the failure of these dams can cause environmental impacts of great magnitude, potentially devastating entire ecosystems. Given the large number of dams in Brazil and especially in Minas Gerais, it is essential to understand the impacts of these dam failures to support decision-making, and in the process of licensing, monitoring, and inspecting these facilities.

Analyzing the historical records of tailings dams in Brazil, the collapse of the Pampulha dam in 1954 in Belo Horizonte, Minas Gerais, is particularly notable. Although it did not result in deaths or injuries, several families were displaced, and there was significant environmental damage (Flamini, 2022). In 2014, the failure of the Itabirito dam, also in Minas Gerais, resulted in the deaths of three people and environmental damage. One of the most significant environmental disasters occurred in 2015 with the collapse of the mining dam in Mariana, Minas Gerais. This incident led to the pollution of the Rio Doce, one of the most important rivers in the country, along more than 650 km, affecting over a million people (Fernandes *et al.*, 2016; Hatje *et al.*, 2017; Garcia *et al.*, 2017). It is considered the largest environmental catastrophe in Brazilian history, impacting the water supply, fishing, and agricultural activities of local communities (Zago *et al.*, 2019). Four years later, on January 25, 2019, the collapse of Brumadinho Dam contaminated the São Francisco River, the largest entirely Brazilian river, leaving hundreds of people missing and affecting numerous downstream communities (Campos-Silva; Peres, 2019).

Environmental accidents lead to changes in environmental management policies and practices. Laws in this context aim to protect the ecosystem and society. Faced with the possibility of tragedies related to tailing dam failures, these laws primarily seek to prevent environmental impacts. When prevention is not possible, efforts focus on mitigation and compensation for the consequences, as well as holding those responsible accountable.

The safety of dams is monitored and regulated by the National Dam Safety Policy (PNSB) established by Law No. 12,334, of September 20, 2010. The law provides definitions and guidelines regarding the monitoring and inspection processes of dams (BRASIL, 2010). Furthermore, it establishes a classification system for dams based on the risk and potential damages associated with them (art. 6).

An environmental disaster such as a collapse of a dam has several legal implications related to environmental law and safety, health, and human dignity.

The Federal Constitution of 1988 (CF, Portuguese acronym) in its Article 1, item III, places the dignity of the human person as one of the foundations of the Federative Republic of Brazil (Brasil, 1988). Article 5 guarantees the safety of Brazilians and foreigners residing

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in the country, as well as ensuring compensation for damages caused. Additionally, Article 225 of the Constitution embodies the principles of environmental law, emphasizing the right to an ecologically balanced environment that promotes quality of life for all.

Even before the 1988 Constitution, the most milestone in Brazilian environmental legislation was instituted with the National Environmental Policy (PNMA, Portuguese acronym), promulgated by Law No. 6,938. This policy aims to preserve, improve, and restore environmental quality, ensuring the protection of human dignity, among other objectives. To this end, the policy discusses principles, provides definitions, guidelines, and duties, and presents its instruments (Brasil, 1981). The PNMA establishes principles, standards, and criteria for licensing effective or potentially polluting activities, such as mining. One of the principles in the licensing process for these projects is the principle of prevention when secure elements indicate that the activity is dangerous (MILARÉ, 2018). This preventive guidance is established by CONAMA Resolution No. 1 of January 23, 1986, which sets forth the fundamental criteria and general guidelines for conducting environmental impact assessments (CONAMA, 1986). When the impact is not avoided, environmental civil liability applies, which has as its primary basis the principle of full reparation. This principle mandates that any damage caused to the environment must be completely restored. In situations where there is no possibility of repairing the damage, the corresponding compensation will be given (Milaré, 2018).

To understand the environmental impacts that were not avoided, evaluating corrective actions, fines, and compensation is essential for a comprehensive assessment of the affected areas and the resulting changes to the landscape. In this regard, the application of geotechnologies facilitates the assessment of spatiotemporal changes in land use, providing precise data and generating information that quantifies and qualifies environmental conditions. This assists in effective territory management and planning (Valerio Filho; Cuambe, 2017), aiding decision-making processes concerning socio-environmental impacts. Consequently, the analysis of space-time relationships, including the study of spatial evolutions over time and their unique characteristics, proves crucial for informed management and decision-making.

The objective of this research was to conduct a temporal analysis of changes in land use and cover within the area impacted by tailings subsequent to the rupture of Dam I connected to the Córrego do Feijão mine in Brumadinho/MG, employing geotechnological methodologies. In addition, the study aimed to understand the extent of the socio-environmental repercussions caused and evaluate the environmental regulatory infringements within the domain of environmental law.

METHODS

The dam is located within the municipality of Brumadinho in Minas Gerais and is a part of the Iron Quadrangle region (Diniz *et al.*, 2014). The municipal area covers 639.434 km² and has a population of 39,914 individuals, according to the most recent census data (2022). The study area was defined based on the directly affected region identified by the contour of the mud extension. The primary affected watercourse is the Paraopeba River, a major tributary of the São Francisco River, spanning 546.5 km. Its source is located in the municipality of Cristiano Otoni, and it flows into the Três Marias reservoir (**Figure 1**).

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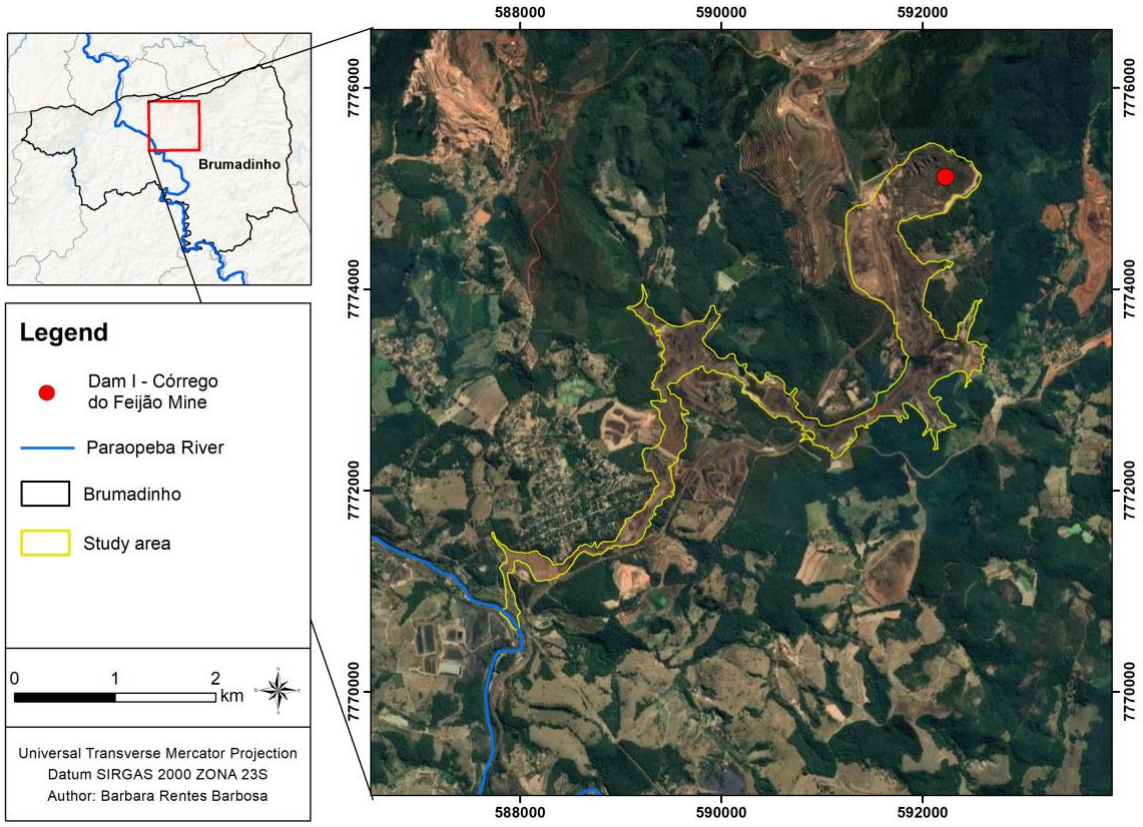
Figure 1. Location of the study area.



Source: The authors, 2024.

The method consists of obtaining secondary data, processing orbital data, land use mapping, and analyzing the results, divided into two stages.

The first stage involves land use classification to observe changes over time, which includes creating a database with satellite images to establish a land timeline of use before and after the event, and generating thematic land use maps of land use. Three images were used: the first scene corresponds to the moment just before the breach on January 24, 2019. The second scene depicts the immediate aftermath of the breach on February 23, 2019, when the impacts were widespread, and the third scene shows the situation six months later, on July 26, 2020. The images were processed to enhance the visibility of features by adjusting contrast and applying filters.

The scenes are available on the Planet Web Platform (https://www.planet.com/products/platform/?utm_campaign=discovery-brd&utm_source=google&utm_medium=paid-search&utm_content=homepage) captured by the PlanetScope Satellite. The satellite products consist of basic analytical scenes with a high spatial resolution of three meters, enabling the identification of surface details, a 16 bits radiometric resolution, and daily temporal resolution for both short- and long-term monitoring. These characteristics are ideal for processing tasks such as land use classification (Planet, 2020).

The land use classification was conducted manually by vectorizing polygons of the classes of interest at a scale of 1:2,000. Interpretation of different classes considered colors, shapes, sizes, and textures. Initially, the area directly affected by the mud was delimited and

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used as a reference for classification before and after the event. Ten classes were considered: infrastructure (road network, industrial and mining structures outside urban areas), urban area, native vegetation, pastures or exotic grasses, agriculture, bare ground, river (first stretch of the Paraopeba River), and lake or pond. In addition to orbital images, Google Earth Pro images were used to validate the classification. The database was evaluated using Quantum GIS (Geographic Information System).

The second stage involves a qualitative analysis primarily focusing on the environmental impacts resulting from the event within the scope of environmental law. This phase consisted of understanding the environmental legal requirements that were violated through a literature review combined with the results of the analyses from the first stage.

This descriptive analysis considered rights and duties grounded in the Federal Constitution (1988), the National Environmental Policy, the National Dam Safety Policy, the Environmental Crimes Law, as well as CONAMA resolutions, ordinances, and deliberations related to the context of the Brumadinho tragedy. These were further explored to substantiate inferences regarding non-compliance with legislation due to the social and environmental impacts following the dam breach.

RESULTS AND DISCUSSIONS

The total area directly affected by the mud after the disaster is 306.95 hectares, which before the disaster **(Figure 2)**, was predominantly composed of native vegetation, representing 45.9% of the area (140.82 hectares). This was followed by infrastructure, comprising 30.8% (94.55 hectares). Pasture or exotic grasses represented 9.5%, agricultural use 7.2%, urban areas 2.5%, and water bodies 3.5% (Table 1).

Table 1. Quantitative analysis of the land use classes derived from the mapping before the dam failure.

Class	Area (ha)	Area (%)
Agriculture	22.19	7.2%
Urban area	7.62	2.5%
Pasture	29.05	9.5%
Infrastructure	94.55	30.8%
Lake or ponf	9.60	3.1%
River	1.37	0.4%
Bare ground	1.76	0.6%
Native vegetation	140.82	45.9%
Total	306.95	100

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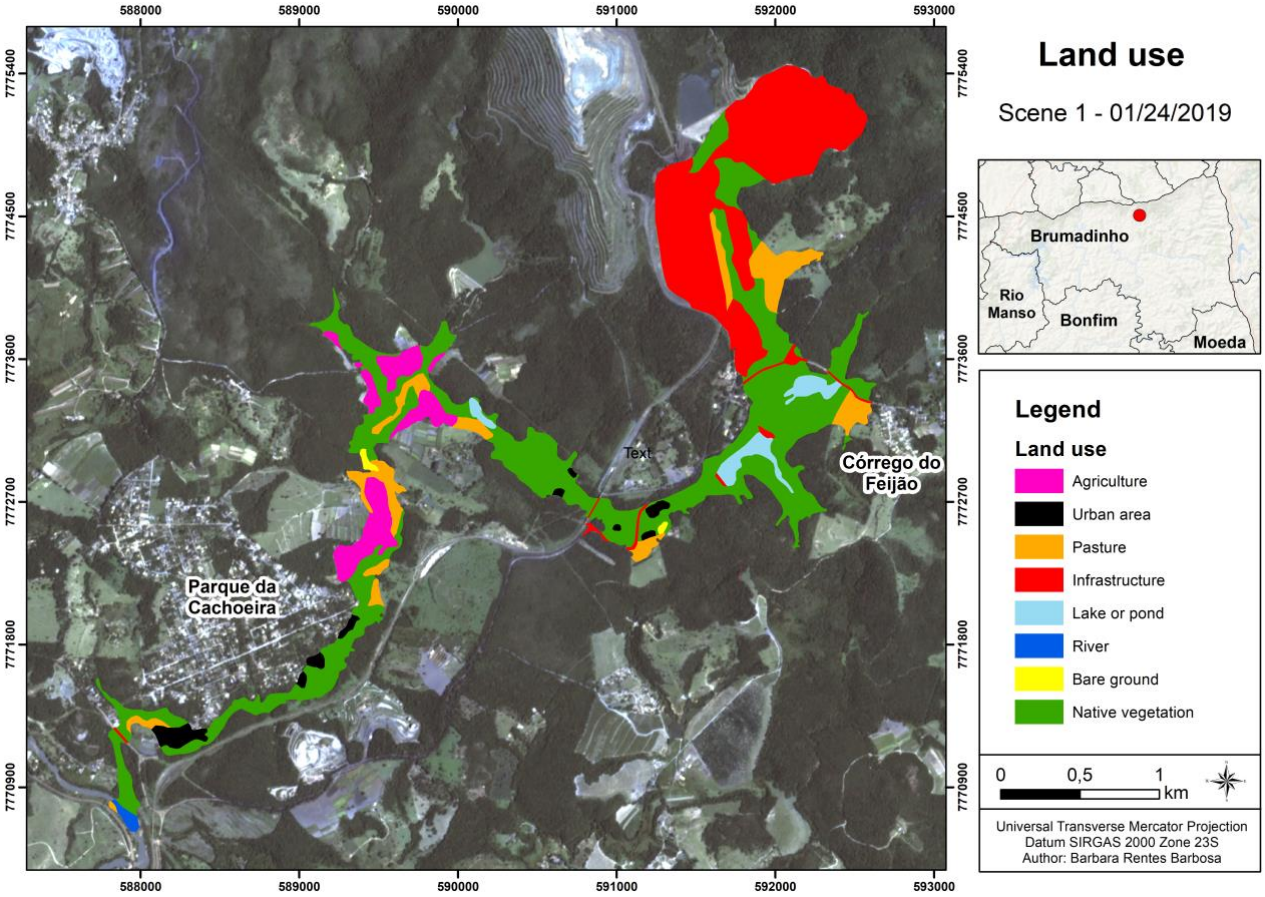
Figure 2. Land use before the dam failure.



Source: The authors, 2024.

The post-breach period reveals a scenario of drastic land use change with the release of approximately 12 million cubic meters of iron ore tailings. The results show that a large area of infrastructure and urban space was destroyed. Our mapping indicates that the tailings directly impacted around 98 buildings, including family residences, guesthouses, and corporate structures **(Figure 3)**.

In the 60 days following the breach, the water in the first 40-kilometer stretch (starting from the failed dam) was considered unsuitable for various uses due to the significant concentration of iron ore (IGAM, 2020).

After a year and a half, no significant changes were identified in land use compared to the post-disaster situation **(Scenes 2 and 3, Figures 3 and 4)**. The tailings continue to occupy the disaster-affected area. Particularly noteworthy is the reconstruction of the road to Alberto Flôres, connecting Brumadinho to other rural neighborhoods, stands out as crucial for the local population **(Figure 4)**.

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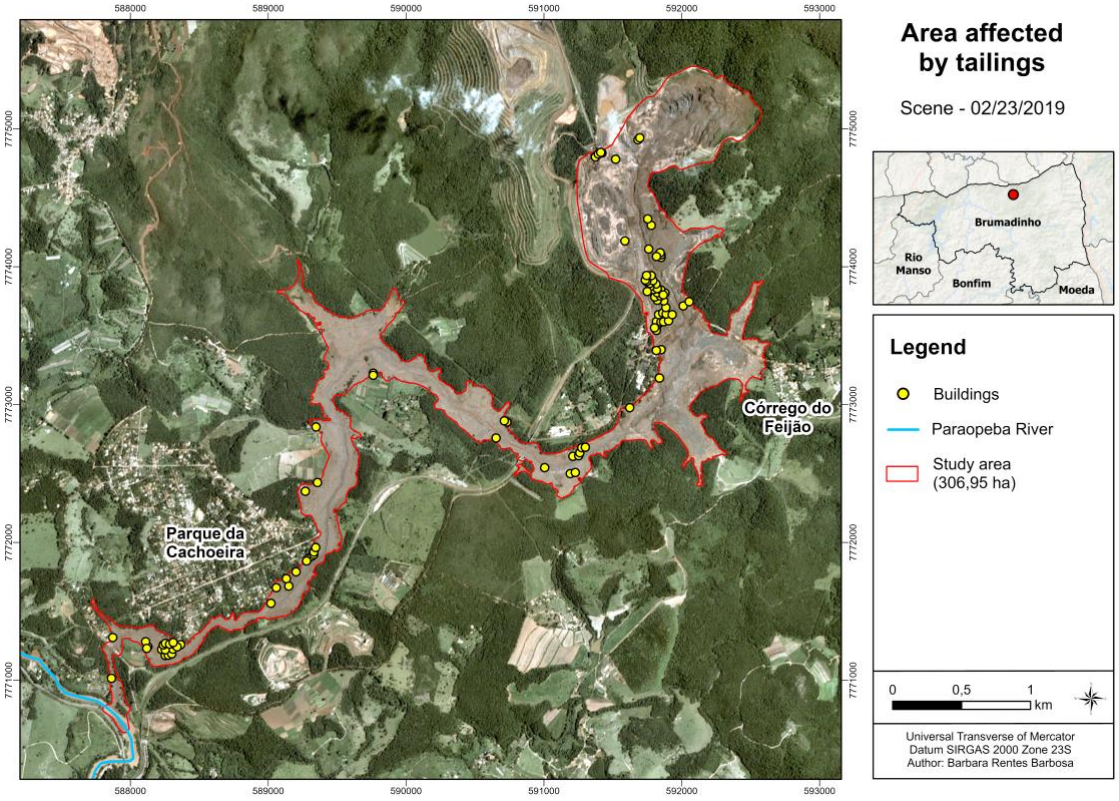
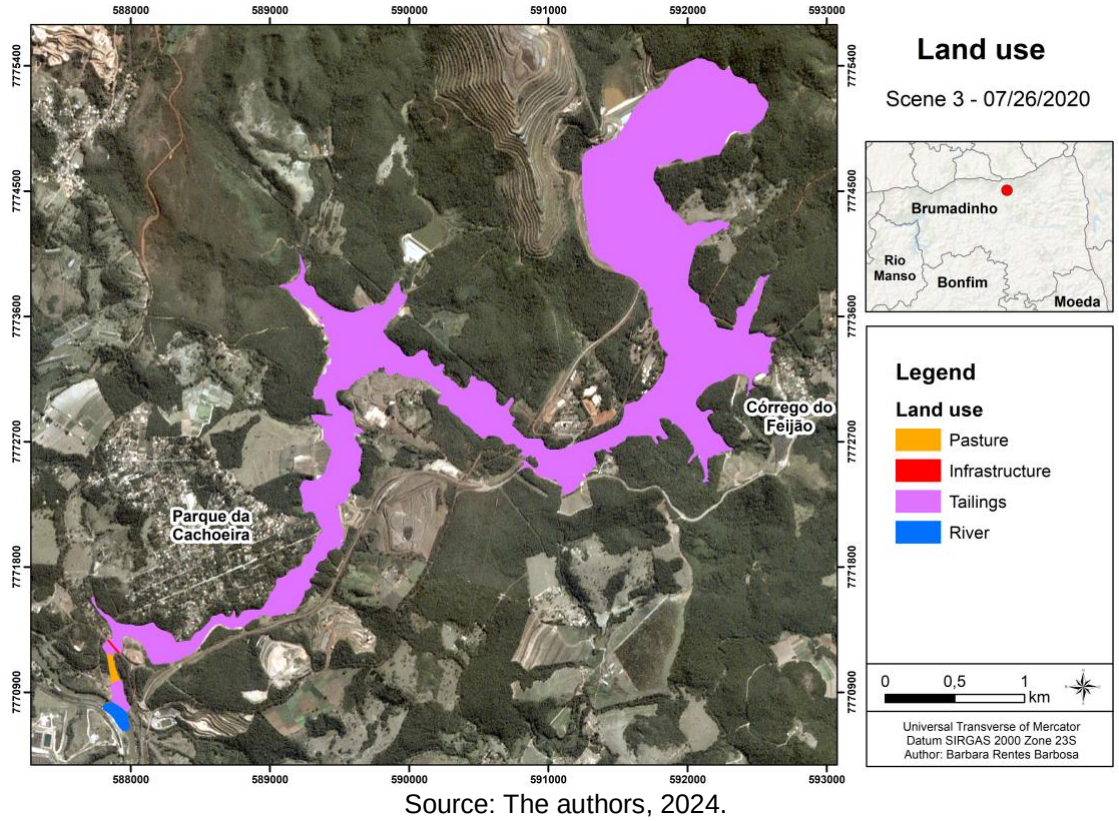
Figure 3. Area affected by tailings after the dam breach and location of destroyed buildings.



Source: The authors, 2024.

Figure 4. Land use one and a half years after the breach of Dam I.



Source: The authors, 2024.

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Among the direct consequences of the dam breach, a significant one is the contamination of watercourses due to the discharge of 2.8 million cubic meters of tailings directly into the Paraopeba River (Stariolo, 2023). An analysis of water quality from 2004 to 2018 in the sub-basin of Ferro-Carvão stream, a tributary of the Paraopeba River, using reference values established in Deliberation Normative Copam/CERH-MG nº 1/2008, found that manganese and iron levels exceeded legal standards during rainy periods, with non-compliance rates of 99% and 1% respectively. This could be associated with mining activities and contributions of undefined origin through soil leaching processes. Lead concentrations showed 1% non-compliance, while mercury values were within legal limits (Arcadis, 2023a). After the breach, a new assessment of the Paraopeba River water quality by the municipality of Brumadinho indicated total lead and mercury quantities 21 times above acceptable levels (IGAM, 2019). Other studies also reported increased levels of iron, aluminum, manganese, zinc, copper, and cadmium exceeding Brazilian regulatory limits (Thompson *et al.*, 2020; Vergilio *et al.*, 2020).

The mud, upon reaching the water body, causes the extermination of habitat along its entire course, decimating fish populations and ichthyofauna, likely due to increased water turbidity caused by the tailings, which probably led to the suffocation of animals (Lopes, 2016). According to emergency monitoring conducted by IGAM after the dam breach, the Paraopeba River recorded turbidity levels of up to 34,500 NTU, which is 58 times the maximum value previously established in the watershed diagnosis, a document prepared by Arcadis, hired by Vale to implement the Socio-Environmental Repair Plan. Daily monitoring data of fish carcasses in the Paraopeba River indicate that approximately 7,000 carcasses were collected in the first fifteen days of monitoring. Most were collected after the rainy period, which resulted in sediment and tailings movement and released buried carcasses (Arcadis, 2023b). Moreover, this event led to the lack of potable water supply and increased environmental toxicity due to heavy metals in the mud composition, compromising basic infrastructure such as road networks and energy supply, as well as the livelihoods of the community living along the river, which depended on available ecosystem services (Rodrigues, 2019).

The ore tailings reached fertile soils, leading to geochemical contamination. Upon drying, the mud forms a thick, dense, and low-clay layer, physically impeding agricultural practices, thereby affecting the economic and subsistence activities of local populations that depend on the affected natural resources (Silva *et al.*, 2016).

One and a half years after the disaster, the land use in the affected area (306.95 hectares) still retains the tailings, continuing to impact water resources and consequently affecting the communities dependent on them. The loss of 140.82 hectares of native vegetation, accounting for 46% of the affected area, hampers the slow recovery of the river. Actions to restore native vegetation are crucial for the recovery of watersheds (PIRES *et al.*, 2017).

Human losses were the greatest immediate impact, primarily linked to the location of the dam near the company's administrative facilities and residential areas of the Parque da Cachoeira Community (Pereira *et al.*, 2019). As our analysis shows, 98 buildings were buried. The affected families experienced socio-economic losses, and the entire spectrum of socio-environmental impacts will affect the psychological, psychiatric, and psychosocial conditions of the victims (Carvalho, 2017; Coelho, 2019; Neves *et al.*, 2018).

Legislation based on a command and control system is a tool aimed at protecting humans and the environment, particularly against polluting activities or those with pollution

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potential, such as mining activities. Hence, the monitoring process is essential for the orderly functioning of this system to propose mitigation measures and dam safety. In the National Dam Safety Policy (PNSB), Article 3 explicitly emphasizes concern for damage prevention based on the "principle of prevention" establishing safety standards for structures. In this context, the dam breach highlights negligence towards this principle and the law. Violating a principle is more critical than violating any other norm because lack of attention an compromise the entire command system (Milaré, 2018).

The Brazilian Constitution establishes security as a fundamental right under Article 5; however, this was respected in the face of the 270 victims who lost their lives in the accident. Furthermore, Article 225 of the CF emphasizes the right to an ecologically balanced environment, which can be reconciled with economically impactful activities through the application of appropriate measures for mitigation, compensation, and environmental monitoring, alongside rigorous oversight, responsibility, and non-negligence in maintaining activity needs. The devastation of 140.82 hectares of native vegetation represents an immeasurable loss of buried biodiversity that previously served ecosystem balance functions, indicating a violation of the aforementioned law. This article holds perpetrators accountable for numerous harmful actions and damages caused by the dam breach, subjecting them to criminal and administrative sanctions, with considerations not only for the environment but also for society at large.

The PNMA aims to ensure dignity of human life (BRASIL, 1981), a right also explicitly stated in the 1988 Brazilian Constitution, Article 1, Section III. The destruction of homes and infrastructure totaling approximately 7.62 hectares disrupts the sense of unity, causes suffering, and exacerbates existing difficulties in the lives of the victims and their families, thus violating the principle of human dignity.

The Environmental Crimes Law holds offenders accountable in administrative, civil, and criminal domains. Criminal environmental protection intervenes only in cases like the one exposed, where fundamental societal values have been intolerably violated.

This study recognizes that the events in Brumadinho also suggest violations of other principles and laws beyond those mentioned, such as the Native Vegetation Protection Law and the Atlantic Forest Law, constituting primary study areas. Given the numerous norms and principles violated, the obligation for full reparation of the damage caused by the offenders remains.

The president of Vale, along with 15 others including directors, managers, geologists, engineers, and consultants from the mining company, have been accused and are facing trial for 270 counts of qualified homicide and crimes against fauna, flora, and pollution. Vale and Tüv Süd Bureau de Projetos e Consultorias Ltda, responsible for technical supervision, are also accused of environmental crimes (Rei, 2020).

In February 2021 an integrated solution agreement was reached with Vale for full reparation, totaling a global amount of R$37.68 billion (Brazilian Reais – BRL). This encompasses the sum of specified obligations in the agreement. Thedamage reparation measures are divided into four parts: the Socioeconomic Repair Program defining actions in Brumadinho, directly affected communities, and 25 other impacted municipalities; the Socioenvironmental Repair Program involving interventions for recovery and compensation of known and irrecoverable environmental damages; the Mobility Program aimed at improving road infrastructure throughout the state of Minas Gerais; and the Public Service Strengthening Program focusing on improvements in health, economy, security, labor, and

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technology (Minas Gerais, 2021).

As of December 2023, approximately 6,104 individual agreements involving 12,522 people and 1,487 employment-related agreements involving 2,509 people were concluded. These agreements allowed all individuals affected by the dam breach to request various types of compensation: either individually or related to employment. The environmental recovery, including the implementation of a Socioenvironmental Repair Plan, is estimated at R$ 6.55 billion without a financial cap (VALE, 2024).

CONCLUSION

The mapping provided a spatial and quantitative view of the damages caused by the dam breach, offering an understanding of the extent of the impacts generated. It is noteworthy that the directly affected area encompassed 140.82 hectares of native vegetation, followed by infrastructure areas including company facilities, housing, access roads linking neighborhoods, and agricultural lands. Even one year after the event, the impacted area shows no signs of recovery in native vegetation or productive areas, indicating irreversible environmental and economic impacts for the Paraopeba River watershed.

Furthermore, the disaster resulted in legal implications related to fundamental rights such as population safety, human dignity, and prevention. It is relevant to highlight that policies aimed at dam safety and society's access to an ecologically balanced environment were neglected.

The significant changes in local land use, impacts on the community of Brumadinho and surrounding areas that also suffered losses, particularly from the arrival of tailings through the Paraopeba River, along with their socio-environmental consequences, underscore the need to defend society's rights and demand stricter supervision and oversight from competent authorities, as well as compliance with regulations by the companies involved.

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