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Deterritorialization of Hydrographic Basins due to Hazards and Environmental Contamination - a Case Study in Minas Gerais (Brazil)

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R E S U M O

Population movements or loss of territories occur in the context of hazards and environmental contamination because the menace or the beginning of danger makes the residence region temporarily or permanently uninhabitable. In certain localities of Minas Gerais (SE Brazil), the social-economic development is challenged by the growing complexity of the risk and hazards occurrence, as well as causality issues, inadequate information, and lack of capacity and responsibility. Tailings dam failure is considered as the major environmental hazards worldwide. The Mariana and Brumadinho disasters (Brazil) are marked by the extent, magnitude and complexity of the resulted losses and damages. The frequency of the events on a world scale, the number of casualties at the event time and later the irremediable damage to ecosystems, the magnitude and complexity of losses, and the social and political uncertainties that are installed reveal about the hazard magnitude. Water, soil, and sediment contamination by arsenic (As) is a problem in more than 70 countries and affects more than 140 million people due to risk to human health associated with As-contaminated water and food intake, including carcinogenic effects. The dissolution of As-bearing minerals associated with gold mineralization and the produced tailings on mining activities promotes an increase in As concentration in soil, sediments and water. The main objective of this study is to assess the loss of territories by vulnerable populations settled in scenarios related to tailings dam failure and submitted to the consequences produced by water, soil and sediment contamination.

Keywords: Dam breaks, Mining, Arsenic, Loss of Territories, Water Pollution.

Deterritorializacion por Contaminación Ambiental y Desastres en Cuencas Hídricas - Estudio de Caso en Minas Gerais (Brasil).

R E S U M E N

El desplazamiento de poblaciones o la pérdida de territorios se produce en el contexto de desastres y contaminación ambiental porque la amenaza o la ocurrencia de la aparición del peligro hace inhabitable, temporal o permanentemente, la región de residencia de una población. En ciertos lugares de Minas Gerais (SE de Brasil), el desarrollo socioeconómico se ve desafiado por la creciente complejidad del riesgo y la ocurrencia de desastres, así como por problemas de causalidad, información inadecuada, falta de capacidad y responsabilidad. Consideradas como las mayores catástrofes ambientales relacionadas con fallas en represas de relaves en Brasil, y una de las mayores del mundo, las catástrofes de Mariana y Brumadinho llaman la atención sobre el alcance, la magnitud y la complejidad de las pérdidas y los daños resultantes. La contaminación de aguas, suelos y sedimentos por arsénico (As) es un problema en más de 70 países y afecta a más de 140 millones de personas debido a los riesgos para la salud asociados al consumo de agua y alimentos contaminados con As, incluidos los efectos cancerígenos. La disolución de los minerales que contienen As asociados con las minas de oro y sus relaves provoca un aumento en las concentraciones de As en el suelo, los sedimentos y en el agua. En este contexto, el objetivo de este trabajo es evaluar la pérdida de territorios por parte de poblaciones vulnerables asentadas en escenarios de desastre de ruptura de la presa de residuos tóxicos y sometidas a las consecuencias que produce la contaminación de aguas, suelos y sedimentos.

Palabras clave: Rotura de presas, Minería, Arsénico, Pérdida de Territorios, Contaminación del Agua.

Introduction

Thought and formatted as 17 Sustainable Development Goals (SDGs) and 169 Targets, the 2030 Agenda places the Earth planet, people, prosperity, and peace at the center of attention (ONU, 2015). The Agenda's SDG 3 – *Good Health and Well-Being* – promotes healthy life by seeking well-being for all the people with different age. In turn, SDG 11 – *Sustainable Cities and Communities* – suggests the transformation of cities and settlements in more secure, resilient, and sustainable places. The concept of deterritorialization is the physical and geographical dematerialization of social processes. For Haesbaert (2004), deterritorialization corresponds to a loss of spatial references (not loss of space) and to a process of loss of autonomy and freedom in the symbolic and functional appropriation of the geographic space and consequent social and psychological crisis, with mismatches of identity and economic affirmation.

New technologies applied to communication have shortened the distance and devaluated the role played by the main elements of the spatial dimension: the spatial location and distances. Without the true observance of space as a fundamental entity and with a singular devaluation of the geopositioning sciences, the processes and economic activities search for the "creation" of a flat world (Friedman, 2005). Therefore, and with the technological innovations, the geopositioning factor would cease to be distinctive and, by itself, would not prevent or boost any development dynamics (Badie, 1995; Guattari and Rolnik, 1996).

Environmental hazards associated to natural and/or anthropic causes (e.g., volcanic eruptions, dam failures, soil and water contamination, forest fires), could mobilize and drive populations away from their home territories, causing acute crises, with direct effects in the community deterritorialization, generating an increase in the vulnerability and insecurity, and potentializing several diseases forms (Fernandes, 2008).

The immediate valorization of human life and health is necessary when it is projected that the population of the urban areas and communities will reach 68 % of the world's population in 2050 (UNDESA, 2018). It is improbable that Earth sustainability and human health will be reached, with the general individual behavior based on rational "selfishness".

In Brazil, of the 425 dams listed in the *Plano Nacional de Segurança de Barragens* (PNSB – National Plan for the Safety of Dams), 107 were built applying the downstream method, 84 the upstream, and 30 the centerline method. The remaining 204 dams were built in a single stage or with a starting dike (ANM, 2019). However, mining tailing dams, could be built via several stages. As the dam is concluded, tailings are disposed. The new impoundment portions are built on top of the previous structure with a new dam crest, following upstream, downstream, or any other direction. The upstream method is the one that leads to the highest number of accidents, with ca. 76 % of the cases recorded worldwide (Aires *et al.*, 2018).

According to the *Agência Nacional de Mineração* (ANM – National Mining Agency), 364 mining tailings dams are located in the State of Minas Gerais and until August 2022, one out of five dams of relevant size or content has not submitted the *Declaração de Condição de Estabilidade* (DCE - Declaration of Stability Conditions) or failed to obtain one. These data are from the agency's *Sistema de Gestão de Segurança de Barragem de Mineração* (SIGBM – Safety Management System for Mining Dams). In 2022, 167 dams of the State of Minas Gerais submitted the documentation elaborated by their own technical staff or by third party experts, necessary to attest stability via the DCE. Nevertheless, three have not sent the documentation within the established deadline and 35 structures do not present the conditions to attest stability within the required technical parameters. In total, there are 768,203.67 million cubic meters of tailings stored, or about nine times the Fundão Dam, in Mariana, and 44 times the B1 dam of the Córrego do Feijão Mine in Brumadinho (Segura *et al.*, 2016).

The State of Minas Gerais stands out for different mineral reserves, including some of the largest deposits, provinces, and mineral districts of Brazil. Historically, ore exploration activities have been developed in whole Minas Gerais territory and have caused several environmental impacts which cannot be underestimated (Carvalho and Almeida, 2018).

In the last decades, the negative environmental impacts associated to the mining activities increase, mainly related to iron ore, have significantly grown. Among the negative impacts related to mining, contamination by arsenic (As) is highlighted. In several parts of the world, as in some localities in Brazil, high total As contents have been detected in surface and groundwater, soils and mining tailings (Gonçalves *et al*., 2007). Records and studies on As contamination have tried to correlate mining activities or natural sources of this element and related effects on the environment and human health (e.g., Carvalho *et al*., 2022; Antunes *et al*., 2016; Neiva *et al*., 2016; Antunes *et al*., 2014; Gonçalves and Lena, 2013).

Some authors suggest that As contamination of water, sediments and soils in Brazil is a natural phenomenon related to the soil composition and has become an environmental problem due to anthropic activities (Teixeira *et al*., 2020).

According to Gonçalves *et al.* (2010), environmental As mobilization occurs by the combination of events that include not only natural processes, such as rock weathering processes, volcanic emissions, and biological activities, but also anthropogenic processes – like the use of pesticides, fossil fuels, and mining activities.

Until few years ago, As was not among the constituents that are routinely analyzed in waters for human consumption, because its distribution was not well-known, in comparison with other physical-chemical elements. For this reason, As occurrence in surface and groundwater for human consumption constitutes a great menace for the public health (e.g., Carvalho *et al*., 2022; Antunes *et al*., 2016; Neiva *et al*., 2016; Antunes *et al*., 2014; Gonçalves *et al*., 2010). Thus, the World Health Organization establishes that drinking water should contain less than 10 $\mu g.L^{-1}$ of As.

Resolution #357 of the *Conselho Nacional do Meio Ambiente* (CONAMA – National Environment Council), from 17th March 2005, establishes a maximum As concentration limits varying from 0.01 to 0.14 $mg.L^{-1}$, according to the nature and the purpose of water use. The Annex I of the Ministry for Health Consolidation Ordinance #5, from 28th September 2017, establishes that the total water As contents for human consumption should be below 0.01 $mg.L^{-1}$.

The objective of this paper is to investigate deterritorialization in the context of mining tailings dam failure and consequent environmental As contamination effects and on human health, particularly on the water and soil associated to Minas Gerais hydrographic basins. This situation, implies the loss of social *locus* by the affected population and will be crucial to define regional public health policies.

Methodology

Firstly, a primary database was created from a bibliographic survey, which gathered peer-reviewed texts in English and Portuguese, published between 2000 and 2022, and indexed in the electronic Web of Science, Scopus and Scielo databases.

Some keywords related to the themes of this study were selected for the first screenings, in any field, within the documents. The selected keywords (search criteria) included: "*loss of territory*", "*displaced populations*", "*dislodged communities*", "*arsenic*", "*Doce River basin*", "*Velhas River basin*", "*Paraopeba River basin*", "*Minas Gerais*", "*contamination*", "*mining*", "*groundwater*", "*water*", "*soil*", "*health*", "*failure*", "*dam*", "*Brumadinho*", "*Mariana*", and "*Fundão*". Keywords combined as duos or trios were also recovered: "*arsenic/Quadrilátero Ferrífero*"; "*arsenic/Minas Gerais*"; "*arsenic/hydrographic basins/Minas Gerais*", "*arsenic/Quadrilátero Ferrífero/Minas Gerais*", "*arsenic/dams/Minas Gerais*", "*dam failures/arsenic/Minas Gerais*", "*hazards/dams/mining*", "*hazards/dislodged populations/contaminations*".

The following information was recorded from the retrieved documents: (a) identification of the authors; (b) date of publication; (c) bibliographic references; (d) thematic area; (e) territory of the research; (f) keywords defined by the authors and included in the papers; (g) number of citations; (h) objectives of the research; (i) information on the mining activity (e.g., location, processed ore or element, open-pit or underground mining, paragenesis, active or abandoned mines); (j) researched matrix (soil, surface or groundwater); and (k) applied methodology.

The database was analyzed quali- and quantitatively and compared to other available scientific documents to be correlated within Minas Gerais region, Brazilian and other international scenarios.

Therefore, a systemic review of the database on hazards related to tailings dam failure and As contamination of Minas Gerais hydrographic basins was performed. The review focuses on English scientific papers, allowing a wider general access to the scientific community. A significant number of documents written and published in Portuguese that are not easily accessible to the majority of the international scientific community, including governmental and non-governmental reports, Brazilian environmental legislation, Brazilian patterns and statistical data, were included in the review as secondary bibliographic source, as the access of the existing international scientific community database on dam failures and As contamination in Brazil is hampered by language limitations.

International studies present has the main objective the characterization of scenarios in specific Brazilian regions. Frequently most of international studies cite the same scientific documents. However, these cited studies could suggest to a false supposition that "this is a recent environmental problem restricted to a very small area".

It is worth mentioning that the major hazards associated to dam failures and environmental As contamination in Brazil have been a long-term environmental and health problems and are widespread over a large area covering a vast area of the country. Three hydrographic basins were selected on this study concerning to the environmental problems mentioned above and the affected population, namely: the Paraopeba River, the Doce River and the Velhas River basins.

Results and discussion

Accidents involving tailings dams not only penalize the mining and industry sectors, but mainly the environment and associated population. As a result, the damage caused to water courses will directly affect the availability and quality of water supply.

Such hazards have led to human losses, environmental damage to the public and private property, besides severe direct and indirect socioeconomic damage to biodiversity and water resources. Mud waves destroyed houses and deeply affected water resources along many kilometers traveled by tailings throughout several municipalities (Coelho, 2009).

The environment is exposed to a variety of impacts, such is the water quality and availability, loss of native vegetation and natural soil, modification of water courses morphology, and terrestrial and aquatic fauna mortality.

The affected population faced countless difficulties to be able to recover economically and psychologically (Queiroz *et al.,* 2018; Gomes *et al.,* 2017). The general capital flow and the various transactions in the market and hotel sectors that were propelled by the jobs generated by the mining companies were strongly affected by the by hazards in the Mariana and Brumadinho regions.

The tailings flow down to Paraopeba and Doce rivers represent a major problem for the population of the municipalities from the hydrographic basins, once these rivers supplied water to these municipalities and consequently the water supply was stopped due to water contamination. Figure 1 represents a flowchart of the social-environmental damages caused by the tailings dam failure, suggesting that the damages are systemic, synergic and dynamic.

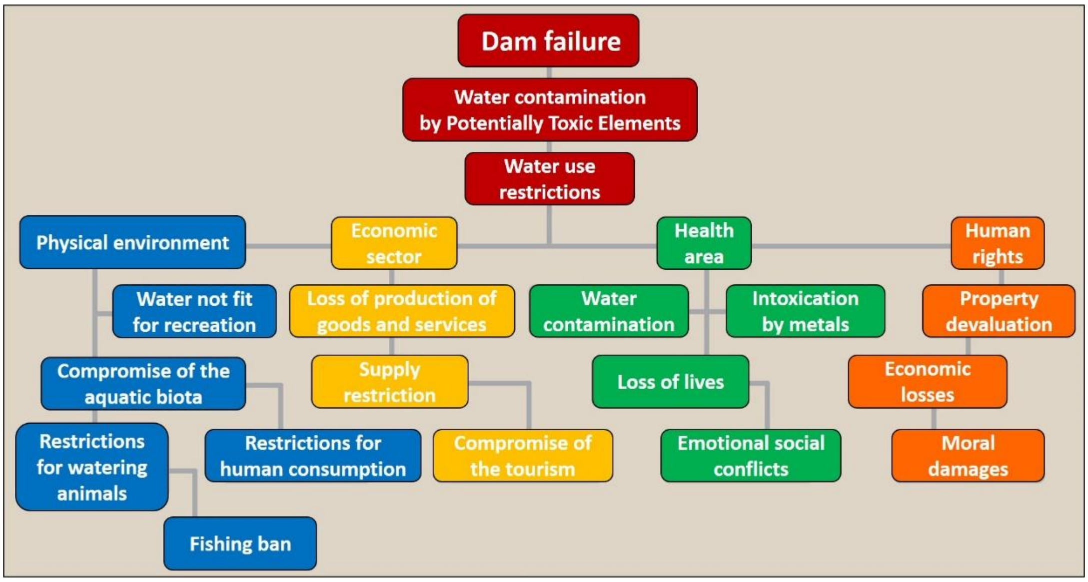

Figure 1. Social-environmental damages resulting from the failure of tailings dams.
Source: Modified after Polignano and Lemos (2020)

In Mariana region, the Fundão Dam failure affected about 236 families from the Bento Rodrigues district, 108 families from the Paracatu district, and the mud reached Camargos, Campina, Ponte do Gama, Barra Longa, Gesteira, and other localities from the Doce River basin. In the total area of the hydrographic basin, about 2,000 families from fishing communities were affected in 41 municipalities, from Mariana to the Doce River mouth in Linhares (State of Espírito Santo). However, it is not possible to estimate fish mortality (Coimbra *et al*., 2019).

In Brumadinho region, the tailings mud reached nine localities with an estimated population of 3,485 people and about 1,090 houses, which represent more than 10 % of the directly affected population. Considering the data from the *Censo Agropecuário* of 2017 (2017 Agropastoral Census) and estimating a radius of 500 and 1,000 meters, along the 18 municipalities crossed by the mud reached the Paraopeba River, it is estimated an extension of approximately 250 km, and 424 communities (e.g., indigenous people, *quilombolas*, foresters, and artisanal fishermen) were affected.

Up to 30th August 2022, 364 dams of the State of Minas Gerais were registered in the *Sistema Integrado de Gestão de Barragens de Mineração* (SIGBM – Integrated Mining Dam Management System), 211 of which were included in the *Plano Nacional de Segurança de Barragens* (PNSB – National Security Plan for Dams), whereas 139 were not considered. Table 1 presents a list of mining municipalities and the associated expressive number of tailings dams.

Table 1. Mining municipalities versus number of tailings dams in the State of Minas Gerais.

Municipality	Population	Number of Dams	Storage Volume (m^3)
Congonhas	54 196	19	18 718 968
Conceição do Mato Dentro	17 641	3	40 952 540
Itabira	119 186	27	417 211 651
Itabirito	51 281	31	87 046 024
Nova Lima	93 577	26	50 573 645
Paracatu	92 430	32	624 456 119
Ouro Preto	73 994	32	138 222 871
Rio Acima	10 203	8	10 500 281
Total	512 508	178	1 387 682 099

3.1. The Paraopeba River Watershed

The Paraopeba River hydrographic basin encompasses the site of the dam failure, the *Ribeirão* Ferro-Carvão and the whole Paraopeba River extension. This includes the region downstream the site of the dam failure, which directly receive the mining tailings, and the region upstream, endowed with strong influence on the water flow and surface and groundwater recharge areas. The basin is located in the Upper São Francisco River and represents 2.3 % of the State of Minas Gerais, with approximately 13,642 km² of drainage area (Pereira *et al*., 2004). The Paraopeba River is the main river of the basin, starting in the Cristiano Ottoni municipality and ending between the Felixlândia and Pompéu municipalities, and flowing into the Três Marias reservoir. The hydrographic basin is composed of 48 municipalities (Figure 2).

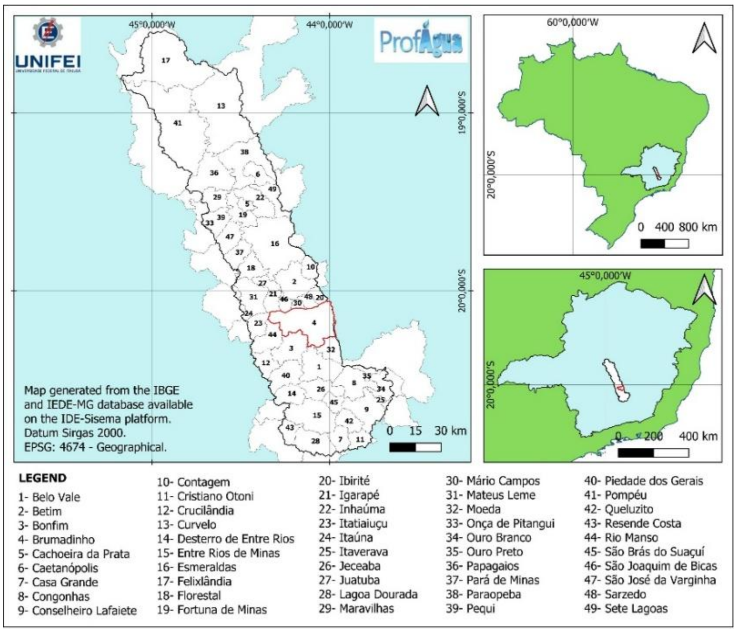

Figure 2. Location map of the Paraopeba River Hydrographic Basin. Source: Modified after IBGE (2010).

Soil type is associated with the geology and the geomorphology of the region. The data obtained and analyzed between 2008 and 2019 (year of the tailings dam failure), the spatial distribution of land use and soil occupation shows that the most perceptive changes occurred in classes that correspond to urban infrastructure, agriculture, planted forest, and pasture throughout the hydrographic basin, with the decrease of the savanna class (Figure 3). As increase in the mining class stands out, which includes piles of tailings/sterile from mining projects, mainly at the sources of the hydrographic basin in Ouro Preto, Itabirito, Congonhas and Belo Vale, where several licensed mining enterprises are located.

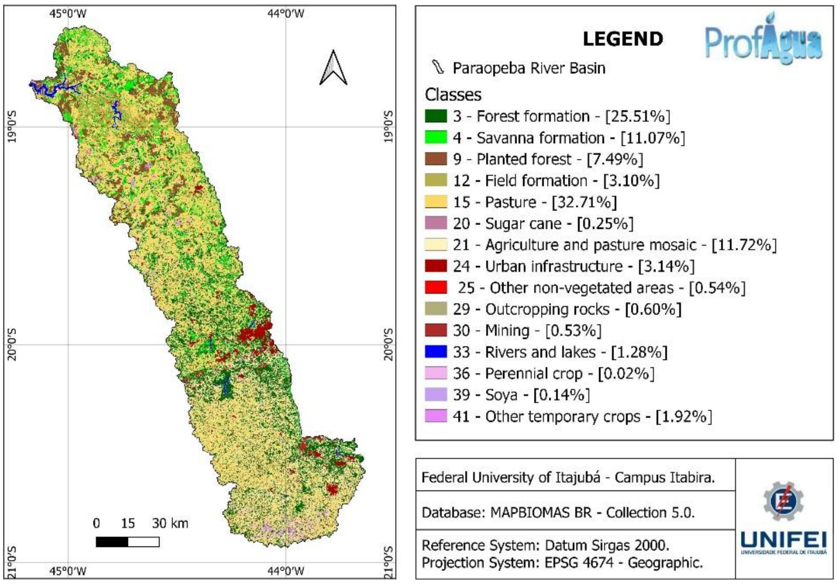

Figure 3. Map of Land Use and Occupation for the Paraopeba River Hydrographic Basin. Source: Modified after IBGE (2010).

On 25th January 2019, Barragem I (B-I) – the tailings dam of the Córrego do Feijão mine from Vale/SA located in Brumadinho – collapsed. Tragically 270 people died and 11 are still missing. According to Carvalho *et al*., (2018), B-I was inoperative for three years and stored a volume of

12 million m^3 of ore tailings. About 2 million m^3 of tailings remained in the area of B-I. *Ribeirão* Ferro-Carvão, which corresponds to the region downstream of the failure site, was filled with approximately 7.8 million m^3 of tailings. The remaining 2.2 million m^3 reached the Paraopeba River, spreading out up to the backwater of the Retiro Baixo hydroelectric plant, between the Curvelo and Pompéu municipalities (Figure 4).

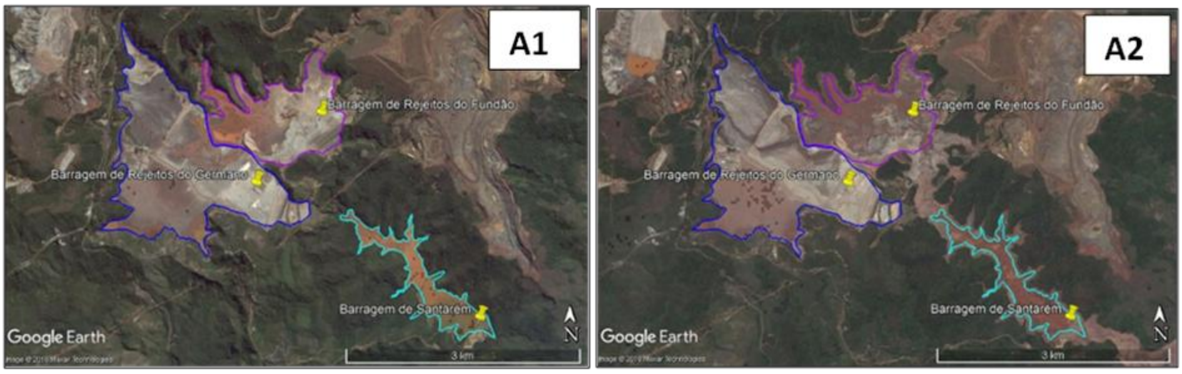

Figure 4. Barragem I (B-I) in Brumadinho before (A1) and after (A2) it collapsed. Source: Modified after IBGE (2020).

3.2. Doce River Watershed

The drainage area of the Doce River hydrographic basin totalizes 86,715 km^2, 86 % located in the eastern part of Minas Gerais and 14 % in the northeastern part of Espírito Santo. The Doce River extends for 879 km. The springs are located in Minas Gerais, in the Mantiqueira and Espinhaço ridges. All the drainage system is important for Minas Gerais economy, supplying water for domestic, agropastoral and industrial use and generation of electric energy. The population of the hydrographic basin is estimated around 3.5 million inhabitants, and is distributed for 228 municipalities – 200 located in Minas Gerais and 28 in Espírito Santo (Figure 5).

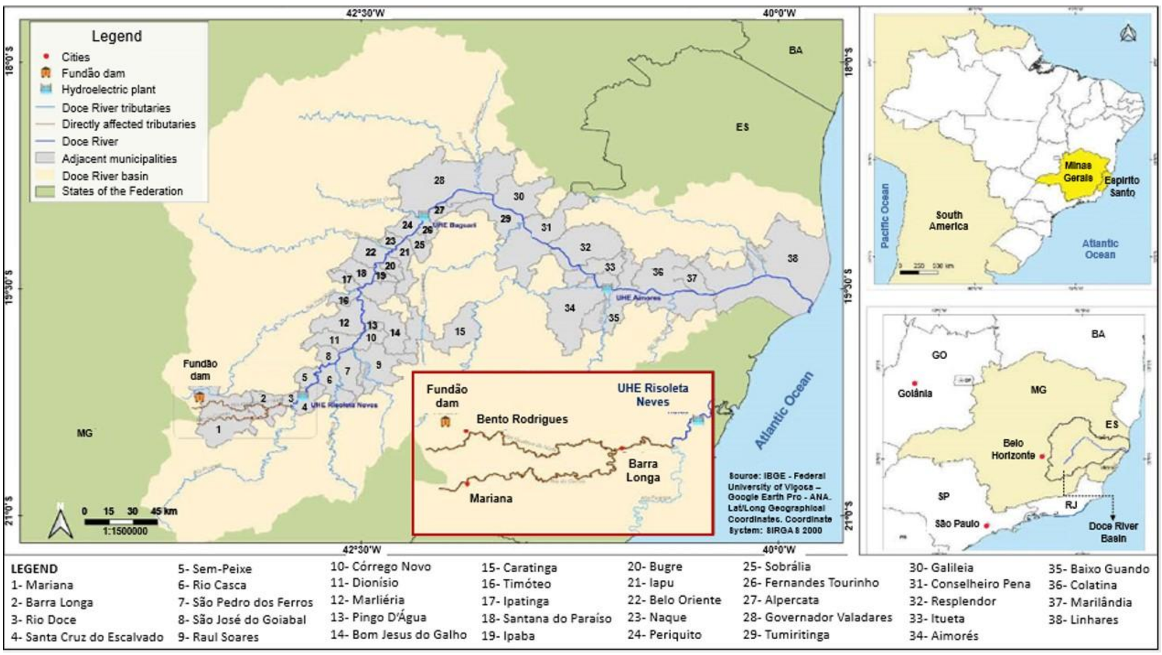

Figure 5. Location Map of the Doce River hydrographic basin. Source: Modified after IBGE (2010).

The territorialization of the Doce River basin is marked by non-sustainable extractive cycles that promote environmental degradation scenarios. In this context, the study of the historical evolution of the territory is crucial to the actual landscape evolution.

The land use profile and soil occupation developed since the 16th century until the present scenario of environmental degradation, the contribution of mining companies into the territory, the social, political and economic character resulting from this process, the expansion of the cities, the installation of steel and industrial complexes, the climate and relief, among other factors, determine the occupation and development of anthropic activities for more than three centuries, resulting in the advance of natural resources exploration and removal of the vegetation for commercial purposes.

The land use dynamic has changed between municipalities marginal to Doce River and non-marginal municipalities before the hazard, and not afterwards, not being detected a direct effect of the hazard (Figure 6). The failure of the SAMARCO/BHP Billiton/VALE dam made the municipalities located marginally to the Doce River more subjected to the limitations imposed by the climate, and in less favorable conditions to the development of agropastoral activities, which led to an increase in the abandonment of these activities (Coelho, 2009). The temperature and mean annual precipitation effect on the abandonment of agropastoral areas is related to the suitability of the climate for these activities. So, the reduced temperature and precipitation represent less favorable climatic conditions for agropastoral activities, leading to the abandonment of these areas (Carvalho and Almeida, 2018).

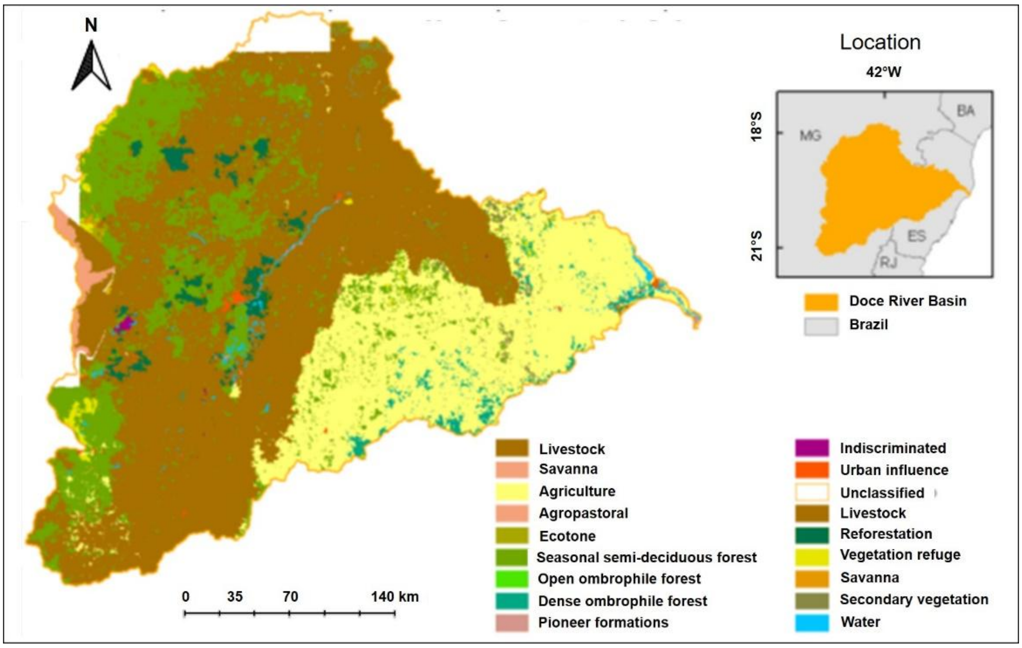

Figure 6. Map of Land Use and Soil Occupation for the Doce River hydrographic basin.
Source: Modified after IBGE (2020).

On 5th November 2015, the collapse of the Fundão tailings dam of Samarco Mining S.A. occurred in the Mariana municipality, with the transposition on the Santarém dam. A volume of about 34 million m^3 of mining tailings, water, and materials from the building have overflown, causing several social-economic and environmental impacts in the Doce River basin (Figure 7) (Queiroz *et al.,* 2018, Gomes *et al*., 2017).

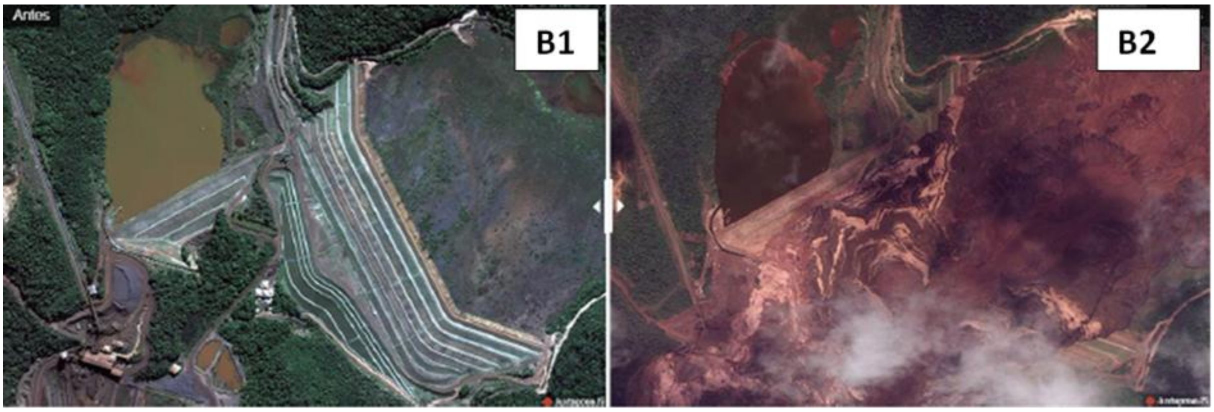

Figure 7. Fundão Dam, before (B1) and after (B2) it collapsed. Source: Modified after IBGE (2020)

3.3. Velhas River Water

The SE-NW-trending Velhas River hydrographic basin is located in the central region of Minas Gerais. The water springs are located within the limits of the Cachoeira das Andorinhas Environmental Protection Area – Ouro Preto municipality. The area of 29,173 km^2 encompasses 51 municipalities that concentrate a total population of 4,885,442 inhabitants (IBGE, 2010), with a contribution of 62 % to the State of Minas Gerais PIB. The Velhas River is essential for Belo Horizonte Metropolitan Region water supply and other municipalities that integrate the hydrographic basin (Figure 8).

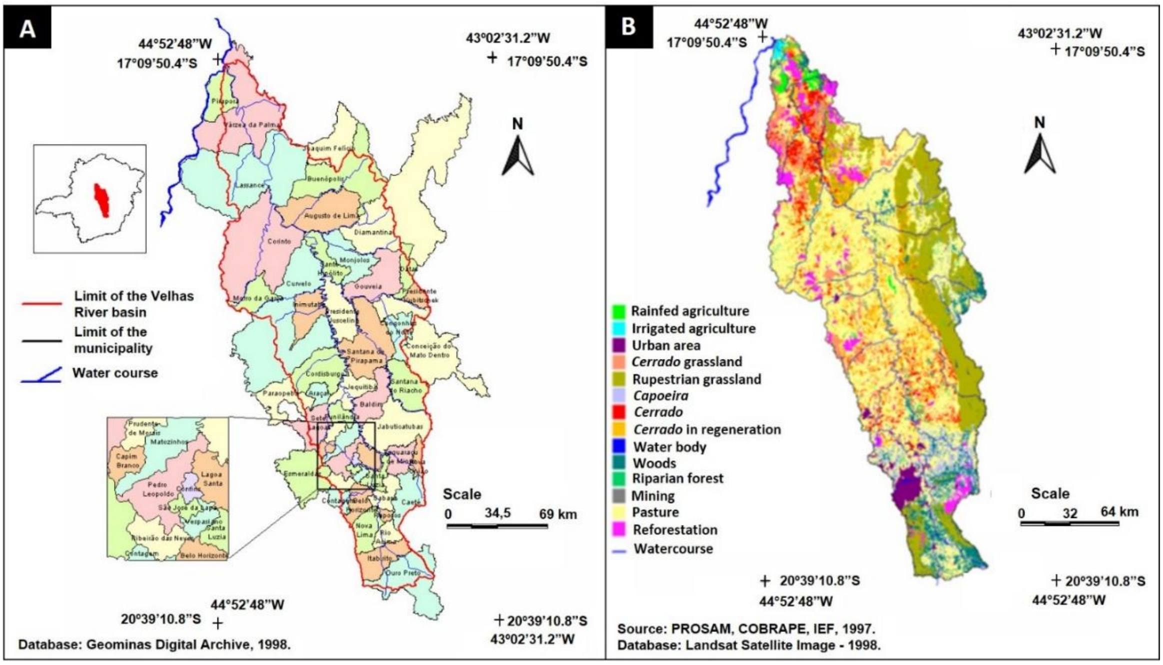

Figure 8. Location Map of the Velhas River basin (A) and Map of Land Use and Occupation (B).
Source: Modified after IBGE (2010).

The Velhas River hydrographic basin represents about 40 % of the exploited water to supply Belo Horizonte Metropolitan Region. This strengthens the relevance of planning and adequate use of the hydrographic basin, as Belo Horizonte is one of the major urban centers of the country, which requires an integrated administration and management aimed to the conservation of the ecological functionality, to maintain and improve water security conditions for inhabitants. The natural cover is represented mainly by *cerrado* (55 %) and seasonal forest (23 %). The region is highly susceptible to erosion (66 % of strong fragility to erosion and 30 % of medium fragility). The temporal land use and soil occupation is visibly observed, as the growth of the urban perimeter demands even larger areas together with mining. This growth is directly correlated with major enterprises both in the mineral and steel sectors, making the perimeters of land use and occupation larger in the hydrographic basin.

3.4. Arsenic in Superface and Groundwater

The presence and evolution of arsenic in water of different sites from the three studied hydrographic basins is considered as a natural origin, temporal and peculiar contamination of each territory. Arsenic water contamination related to the mineral paragenesis of the rocks and associated mineralizations, hydrological regime, geochemical processes, hydrogeological and topographic control. A relevant characteristic of these waters with As contents higher than those permissible for human consumption (Table 2), is the degree of spatial variability of As concentration.

Groundwater presents striking variability in As concentration. During the dry season, with the withdrawal of the water level in the aquifer systems, As groundwater concentration tends to decrease. Otherwise, during the rainy season, with groundwater oxidation-reduction conditions modified by increased precipitation, dissolution occurs and As content is leached and mobilized into the environment, increasing As water content. Therefore, As water contents are representative of the temporal sampling and relative season, and could modified over the time.

Table 2. Minimum and maximum water As contents in Minas Gerais region.

Matrix	As contents		Sampling location	References
	Minimum	Maximum		
Surface Water (μg.L^{-1})	57.7	414	Quadrilátero Ferrífero	Costa *et al*., (2015)
	1,320	2,030	Mariana (Mina da Passagem)	Matschullat *et al*., (2007)
	36.7	68.3	Rio do Carmo	Varejão *et al*., (2011)
	0.4	3,300	Nova Lima, Santa Bárbara	Rodrigues *et al*., (2013)
	0.1	3.0	Belo Oriente, Governador Valadares	Borba *et al*., (2003)
	10.4	50.4	Ribeirão do Carmo	Silva *et al*., (2018)
	78.1	85.3	Rio das Velhas	Silva *et al*., (2018)
			Public fountains, Small Rivers	Pimentel *et al*., (2003)
			Ancient abandoned gold mines	Pimentel *et al*., (2003)
Groundwater (μg.L^{-1})	1.1	10	Belo Oriente, Governador Valadares, Colatina	Carvalho *et al*., (2018)
	9	224	Ouro Preto	Gonçalves *et al*., (2007)
	2	2.980	Ouro Preto	Borba *et al*., (2003)

3.5. Arsenic in Soil

Arsenic soil content of several localities within the studied hydrographic basins is high and exceed the maximum admissible value defined by the environmental legislation (CONAMA, 2019). Dust from contaminated soils could cause toxic effects if inhaled or ingested by humans, in particular children, which are more susceptible to this type of contamination, as a result from their habits. The ingestion of soil has been attested as the most important source of potentially toxic elements contamination (Borba *et al*., 2003; Matschullat *et al*., 2007). Arsenic distribution in soil throughout the study area varies with the intrinsic characteristics of associated lithologies (Table 3).

Table 3. Soil As Occurrence of Minas Gerais region.

Matrix	As content		Sampling location	References
	Minimum	Maximum		
Soils (mg.kg^{-1})	6	900	Mariana	Daus *et al*., (2005)
	46.5	238.7	Ouro Preto	
	200	860	Santa Barbara	Matschullat *et al*., (2000)
	6	925	Ouro Preto	Gonçalves *et al*., (2016)
	13	13,400	Santa Barbara, Mariana	Deschamps *et al*., (2002), Matschullat *et al*., (2007)
	283.2	1,694	Ouro Preto	Santos (2019)
	1,340	3,035	Ouro Preto	Lopes (2014)
	0.25	809	Nova Lima	Menezes *et al*., (2006)

3.6. Arsenic in Sediments

Several studies carried out in the last two decades, including the three presented hydrographic basins, have pointed to high As sediment contents, compared to the reference values defined in the environmental legislation (Table 4).

The assessment of As contamination spatial distribution has been a problem in areas affected by mining, especially of gold, which was attested in the three hydrographic basins and considering both active and abandoned mines.

Besides bottom sediments, the three hydrographic basins contain Quaternary sedimentary deposits, with a possible flow of As and other potentially toxic elements through sediments via surface and groundwater (Cagnin *et al*., 2017). The studies are usually local and concentrated on the impact of the mining activity in soil and water properties, whereas less emphasis has been given to soil and water pollution in these hydrographic basins. The As-contaminated sediments that originated from erosion of the mining areas probably increase the As mass flow.

The dissolved As mass flow must be investigated mainly during the rainy period, because river discharge and sediments in suspension reach peak values, increasing the As mass flow potential, in the dissolved form and also combined to sediments (Davila *et al*., 2020).

Table 4. Occurrences of As in river bottom sediments.

Matrix	As contents		Sampling location	References
	Minimum	Maximum		
Sediments (mg.kg^{-1})	0.63	1.691	Quadrilátero Ferrífero	Costa *et al*., (2015)
	15	3,300	Nova Lima and Rio Santa Barbara	Matschullat *et al*., (2007)
	20	4,000	Velhas River	Borba *et al*., (2000 and 2003)
	30.8	206.7	Velhas River	Silva *et al.,* (2018)
	188.7	521.3	Ouro Preto	Varejão *et al*., (2011)
	203	528	Gualaxo do Norte River	Rodrigues *et al*., (2013)
	28.6	301.9	Carmo River	Silva *et al*., (2018)

3.7. Sediments from the Paraopeba River after the Failure of Barragem I in Brumadinho

The highest Fe content in this period varies between 3.9 wt.% and 39.3 wt.%. The Mn presents a similar behavior, once these elements are the most abundant metals in the tailings. In the first 40 km downstream the confluence with *Ribeirão* Ferro-Carvão, the Mn concentration is very high (0.5 to 2.9 wt.%) after the first monitoring week. The Pb content in sediments, in the first 50 days after the hazard in 2019, is above the reference values. Thus, Pb can be associated not only to the Barragem B1 failure, but also with the activities developed in the hydrographic basin. The As concentration is above the defined on the legislation, and could be associated with the material at the bottom of the Paraopeba River before the collapse of the dam, once As concentration exceeded the permissible values at a point upstream the influence of *Ribeirão* Ferro-Carvão. The high As concentration suggests that should be related to external factors associated to the Barragem B1 failure.

3.8. Sediments of the Doce River after the Failure of the Fundão Dam in Mariana

The physical-chemical characterization of sandy sediments from the Doce River basin reveals a low metal retention capacity. Aluminosilicates and Fe and Mn oxides-hydroxides seem to be dominant species mineral. Sediment potentially toxic elements contents indicate that: 29 % of the Doce River basin samples yielded As concentration above the reference values; 16 %, 18 % and 45 % of the samples yielded, respectively, Hg, Zn, and Cu concentrations above the respective reference values; 100 % of the samples yielded Cr concentration above the reference values, and 93 % of the samples with Ni concentration above reference values (Almeida *et al*., 2018; Carvalho *et al*., 2018; Coimbra *et al*., 2019).

The classification of geochemical quality standards, regarding the origin of the analyzed potentially toxic elements, revealed that As, Hg, Al, Fe, and Mn concentrations are mainly associated to natural weathering processes, which is expected for the three last elements, due to the geological characteristics of the hydrographic basin (Queiroz *et al*., 2018; Gomes *et al*., 2017). Concerning to Hg, no natural Hg-bearing minerals have been found in the hydrographic basin, which suggests an anthropogenic source of contamination. The occurrence of natural As-bearing minerals is detected, mainly in Mariana and Ouro Preto. The presence of Cr, Cu, Ni and Zn should be associated with other sources of contamination, including anthropogenic processes. High Cr concentration was detected in most water samples analyzed.

The residents of the Bento Rodrigues and Paracatu communities were relocated to the Mariana region, after their houses were buried by the dam debris. On the other hand, most of the people from Barra Longa were not relocated, remaining in the city during its reconstruction.

In November 2019, 11 residents of Barra Longa underwent toxicological exams and were diagnosed with Ni poisoning, according to a report from the *Instituto Saúde e Sustentabilidade* (Health and Sustainability Institute), which was sent to the *Ministério Público* (ISS, 2017). Part of the examined people presented altered As levels in their blood.

A year after the accident, part of the mud was removed. A part of it was used in the earthwork of the exhibition park and soccer field, and another one was used as cobblestone. When partially dry, the pavement turned into dust that spread throughout the city with the movement of trucks and heavy vehicles. Some of the symptoms experienced and described at health centers may be related to the exposure of the population to this dust (Vormittag *et al.,* 2018).

The residents of Brumadinho, a month after the collapse of the Córrego do Feijão mine dam in 2018, started feeling the same symptoms of the populations affected by the failure of the Mariana dam, that is, itching and irritated skin, respiratory allergies, and hair loss (Vormittag *et al.,* 2018, Khan *et al*., 2020). In the Paraopeba basin, about 1.3 million people could be contaminated with potentially toxic elements. Due to the toxicity and potential exposition to human activity, it is important to warn the residents about the risks related to land use (Davila *et al*., 2020).

Final Considerations

- ✓ It is evident that in the three studied hydrographic basins the population is exposed to environmental consequences associated to the dam failures, such as As contamination, and consequently have lost their territories or are living under the menace of losing them, with a reality that forces to two types of movements:
  a. Forced Migration, which is the migratory movement with an associated instability element that clearly exposes threats to life or survival by natural causes, that is, people who moved due to natural or environmental, chemical or nuclear hazards, hunger, or development projects;
  b. Displaced People, which are those people who abandon their places or their communities because of fear or for running risks, and are forced to escape due to environmental hazards, either natural or human influenced (Glossário Sobre Migração, 2009).
- ✓ Generally, in Minas Gerais, a fundamental factor for inequalities is in the way people react and these deterritorialization processes are avoided, and also in the way that respond and assert themselves in the necessary reterritorialization dynamics. For a reason,

tradition or habits, the affected communities in these situation have a variety of possibilities and conditions of environmental perception, vulnerability, and responsiveness.

- ✓ The population insecurity is generated by ephemeral or permanent social crises, directly related to the deterritorialization processes. The progress and development of the population occur via the territory, a moving process of change that avoids the deterritorializations, always searching for reterritorialization, trying to reduce excluded people agglomeration, and promoting well-being and broad, general and unrestricted security.
- ✓ Despite the affected people that have lost physical and material territory, their memories, and their sense of belonging, were not lost or even abandoned. The empowerment of the use of the territory comes from the territory construction, in the broader sense of domination and in the symbolic sense of appropriation. And the territory by appropriation is loaded with symbolism, has marks of the "lived", of the use value, and it is this idea of symbolic territory that has been used by the affected as a form of keeping alive the memory of the affected locations.
- ✓ The symbolic and functional territories are not distinct realities, and consequently will be difficult and/or even impossible to analyze a territory without considering these two elements. The strengthening of the sense of belonging and the territorial, functional and symbolic notions have been widespread by initiatives of those affected, with functional interventions in the sub-districts, for example the regular visit to the affected communities and the cleaning of houses or even maintenance of the community cemeteries.

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