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Original Article

The Brumadinho Mining Disaster: Immediate Impacts of Mine Tailings 5 Days After the Dam Rupture

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Abstract

The rupture of the Córrego do Feijão Dam close to Brumadinho municipality is one of the recent and most devastating environmental disaster in Brazil. This study aims to report the results of metal determinations and acute toxicity assays of mining tailing samples collected 5 days after the dam rupture. Concentrations of As, Cu and Ni in site 1 (close to the dam); concentrations of Cu, Zn and Pb in site 2 (Solo Sagrado) and As, Cd and Cr in the three replicates of site 3 (Mario Campos municipality) were higher than TEL reference value. The Cd concentration in of site 1, and As, Cd and Ni concentrations in of site 2 were higher than the PEL reference value, indicating effective effects of these metals to biota. Corroborating with previous studies, the Uranium contamination was detected close to Solo Sagrado. However, the evaluation of radionuclides came to the absence of relevant radioactivity. Regarding the ecotoxicological assays, survivor percentages of *Daphnia similis* were lower than the lab control in sites 2 and 3. Thus, results support concerns regarding environmental recovery, which can take years to occur. Monitoring of biota, abiotic and physical-chemical parameters should be performed continually.

Keywords: Brazil, Minas Gerais, Paraopeba, metal, Córrego do Feijão

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INTRODUCTION

On February 25, 2019, at 12h 28 min, the tailing dam rupture (B1) from Córrego do Feijão has happened in the Brumadinho municipality, Minas Gerais State - Brazil. It was one of the largest tailing disasters of Brazil, causing the worst mining accident in the Brazilian history. The dam was operated by the Vale S.A mining Company, and due to this event, around 12 million cubic meters of iron ore tailings were released into the environment, causing major environmental impacts (Pereira *et. al*, 2019).

The dam started operating in 1976, with the deposition of heights-shaped iron ore tailings, which are the step-shaped tailings deposition, thus forming a large slope. The Dam B1 contained 10 elevations; the last one was deposited in 2013, with a height of 50 meters. After the rupture, the tailings hit the municipality of Brumadinho, over a length of 9 km and 32 km in circumference; followed by the Paraopeba River basis, where the mine tailings flowed and reached approximately 250 km, reaching the São Francisco River and the reservoir of the Três Marias Hydroelectric Power Plant (331 km from the ruptured dam) (Ferraz *et al*., 2019).

Beside the environmental, economic, and social damage, the deaths of more than 300 people were reported, in which 14 bodies have not yet been found due to the scale of the disaster. Many citizens had their homes destroyed by the tailings and had to be evicted (Almeida *et al.*, 2019). According to Freitas *et al.* (2019), 10% of the municipality's population was directly and immediately affected, however this number may be even higher.

The municipality of Brumadinho is located in the state of Minas Gerais, Brazil, specifically in the metropolitan region of the capital, Belo Horizonte. According to the Brazilian Institute of Geography and Statistics – IBGE (2019), the estimated population in 2019 were 40,103 habitants. The Paraobeba River is one of the main sources of income for much of the region's population. The B1 dam was classified as "low risk", but with "high damage potential" according to National Mining agency – ANM (2019), i.e., high pollutant potential. According to the Federal Police report, the power of destruction was warned in several follow-up reports - as the risk of failure was very high (20 times higher than international safety criteria). The likelihood of failure was imminent, since there were no reports proving the proper drainage of the first elevations, made in the initial phase.

The contamination of the Paraopeba River by the tailings of Vale can be noticed through the increased turbidity of the waters and by the presence of a large amount of material in suspension, which caused the death of several aquatic species in the region, making unfeasible the use of the watefor drinking and irrigation plus diminishing diversity in the ecosystem (FIOCRUZ 2019a).

It is extremely important to report the water and sediment conditions just after this dam rupture. Besides the visible changes of the river physical parameters such as turbidity, there is also the presence of high toxicity chemicals, such as metals, since it is well-known that the iron ore exploration may cause contamination by irregular releasing of these elements.

The S.O.S. Mata Atlântica nongovernmental organization (NGO) had sent researchers and technicians to the Brumadinho municipality just after the dam rupture to collect samples of biological and nonbiological materials (such as mining tailings), to assess the primer impacts.

Therefore, this study aims to report and discuss the results of the metal determinations and acute toxicity assays of mining tailing samples collected from the Paraopeba river basis 5 days after the tailing dam rupture (B1).

MATERIALS AND METHODS

The sampling of mining tailings was perfomed by technicians of S.O.S. Mata Atlântica NGO along the Paraopeba river, closer to Córrego do Feijão Dam (Fig.1a,b). Due to the risks to human lives to access the impacted area, only 3 sites could be evaluated.

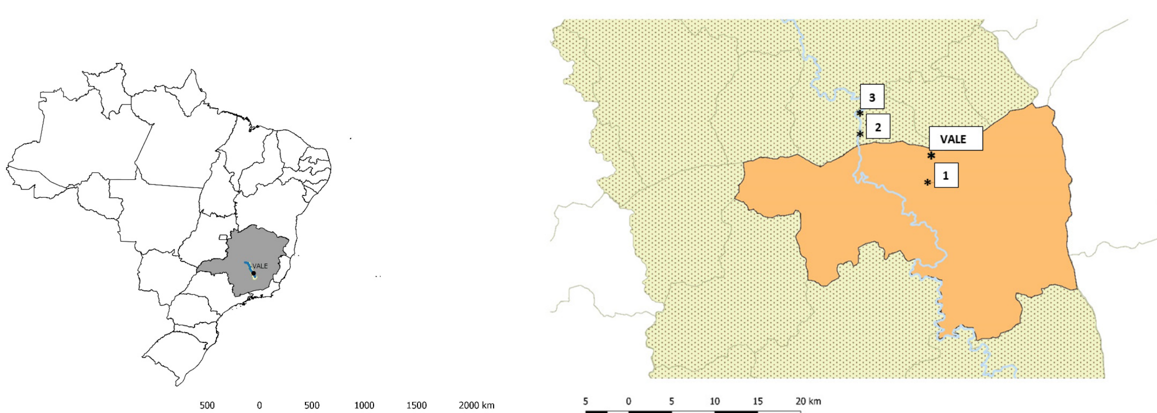

Figure 1. The Minas Gerais State (gray) in Brazil (a) and sampling sites (1, 2 and 3) along the Paraopeba river(b). The location of Vale mining Company was also included.

The site 1 was located closer to the Dam (B1); the second one was in the Pataxó indigenous native community area, called Solo Sagrado, in the São Joaquim de Bicas municipality; and the third site was in the Mario Campos municipality (closer to Brumadinho). In site 3, three sample replicates could be collected, separately. In sites 1 and 3, the group of technicians made a pool of three replicates.

For the determination of adsorbed metals, the collected samples and standard certified material (SRM SS2) were dried in an oven at 40ºC for 4 days. The acid digestion of the dry samples was carried out in a microwave system model MARS 6 (CEM Corporation). The extraction solution consisted of a mixture of 9 ml of HNO_3 and 3 ml of HCl (3: 1), according to the recommendations of the 3051A method (U.S.EPA, 2007). This mixture was added to 0.5g of samples in Teflon flasks, which were properly locked and placed in the microwave system. After cooling, the extracts were transferred to 50 mL-Falcon flasks and the volume was made up with ultrapure water (Milli-Q, 18 MΩ.cm at 25° C). The elements were determined by an optical emission spectrometer coupled with argon plasma (ICP OES -Spectro), from the Chemistry and Environment Center - CQMA / IPEN- SP.Dry samples (150 mg, in duplicate) were also irradiated for sixteen hours, under thermal neutron flux, in the IEA-R1 Research Reactor of IPEN / CNEN-SP. Uranium was determined using the neutronic activation technique (INAA) in the Research Reactor Center -CRPq-IPEN. It is important to highlight that the 3051 A method allows the detection of absorbed metals, while INAA is a nondestructive technique.

Acute toxicity assays with mining tailing samples, using sediment-water interface (SWI) exposure, were conducted at the Núcleo de Estudos em Poluição e Ecotoxicologia (NEPEA) from the São Paulo State University (UNESP), and following the NBR-12173 test protocol (ABNT, 2009). The test-organism was the cladoceran *Daphnia similis*. The tests were conducted in glass tubes of 15mL, containing a 1-cm tailing sample layer and 10mL of clean dilution water. Four replicates were prepared for each sediment sample, and 5 neonates of *D. similis* (maximum age of 24h) were introduced into each test tube. The control consisted of reconstituted dilution water, which was also used in the organism's cultures. The control was also tested in quadruplicates, each one containing 5 neonate individuals. Before the beginning of the tests, some parameters (pH, dissolved oxygen, temperature, and oxy-reduction potential) of the overlying water within the test chambers were measured, by using appropriate sensors.The tests were conducted in a BOD chamber, under photoperiod 8h:16 (dark: light) and constant temperature (20 ± 2 ºC). The experiments lasted 48h, and the test organisms did not receive any food. At the end of the tests, the mortality or immobility rates were observed.

Validation of Methodology and Statistical Evaluations

Metal concentrations were described as Mean±SD. The limit of detection (LOD) was calculated according to INMETRO (2016), as described below:

$$LOD = mean + t_{(n-1;\,1-\alpha)} * SD$$

where mean is the mean concentrations measured in 7 sample blanks, *t* is the *t*- Student value according to the degrees of freedom (n-1) and α=0.05, and SD is the Standard deviation of concentrations measured in 7 sample blanks.

The analytical methodology validation was performed by analyzing the metal recoveries of SRM SS2. The results of metal concentrations in sediment samples were evaluated due to threshold effect levels (TELs) and probable effect levels (PELs) according to CCME (2001). Means were tested applying the Analysis of Variance test (one-way ANOVA) followed by a *post hoc* Tukey test to identify significant differences.

To estimate the sediment toxicities, the survival rates obtained in each sample were compared to that exhibited by the control, by a paired student *t*' test($p<0.05$).

RESULTS

Adsorbed metals

The results of SRM recoveries were considered acceptable and are presented in table 2. According to Method 3051A, elements such as Al and Cr are known as refractory elements, strongly connected to silicates that are difficult to digest and explaining the low recovery of these metals. Silicates may not be dissolved and in some cases may isolate target analyzed elements (Hortellani *et al*., 2008, Bordon *et al.*, 2011,2016).

The one-way ANOVA was performed and the results of metals in the three replicates of site 3 were considered statistically different ($p>0.05$). These results indicate that each mining tailing sample (3.1, 3.2 and 3.3) were not homogenous or similar. Therefore, each replicate of site 3 could be considered as a different sample, although the sampling distance between them were low.

According to the metal concentrations in the collected samples (Tab. 3) and reference values of CCEE (Tab. 4) concentrations of As, Cu and Ni in samples of site 1; concentrations of Cu, Zn and Pb in samples of site 2 and As, Cd and Cr in the three replicates of site 3 were higher than TEL reference value. The Cd concentration in samples of site 1, and As, Cd and Ni concentrations in samples of site 2 were higher than the PEL reference value, indicating effective effects of these metals to biota. Regarding results obtained by

NAA technique in samples of site 2, concentrations of U must be highlighted, since it was higher than the NASC certified values, indicating contamination (Tab. 5). Due to this result, the presence of radionuclides ^{226}Ra, ^{210}Pb, ^{228}Ra e ^{228}Th was investigated by evaluating their activities. Results were considered accordingly to the absence of relevant radioactivity (Tab. 6). However, the contamination of Uranium (U) was identified.

Regarding the ecotoxicological assays, survivor percentages of *Daphnia similis* were lower than the lab control in sites 2, 3.1-3.3 ($p<0.05$) (Fig.2). No statistic differences were observed between site 1 (closer to the dam) and control.

Table 1: Geographical coordinates of sampling sites

Sampling site	Latitude	Longitude
1	-44.130334	-20.14139
2	-44.20876	-20.083019
3	-44.209999	-20.062695

Table 2: Recovery of SS2 SRM.

Metal	Cert ($\mu g\ g^{-1}$)	Mean ($\mu g\ g^{-1}$)	SD	Rec (%)
Ca	112861	108394	4562	96
Co	12	6.13	0.30	51
Fe	21046	21949	1118	104
K	3418	3112	170	91
Mg	11065	10866	1012	98
Na	558	698	29	125
Ag	1.3	1.47	0.10	113
Sn	6	7.83	0.24	130
As	75	49.6	1.0	66
Cu	191	226	2	118
B	12	9.7	0.4	81
Zn	509	536	43	105
Sr	214	230	19	107
Mo	4	4.1	0.7	102
V	34	24	1	71
Ti	850	780	82	92
Cd	2	2.5	0.1	124
Cr	34	22.2	1.4	65
Pb	126	141.5	13.5	112
Mn	457	510	38	112
Li	20	22.6	0.8	113
Ni	54	35.1	1.4	65
Al	13265	12432	1093	94

Legend: SD – Standard Deviation

Table 3: Metal concentrations (µg g-1) in sediment samples collected in sites 1- 3 (mean±SD, max and min)

Site	Metal concentrations (µg g-1 ; % for Fe and Al)																					
1	Ca	Co	Fe %	K	Mg	Na	Ag	Sn	As	Cu	B	Zn	Sr	Mo	V	Ti	Cd	Cr	Pb	Mn	Li	Ni	Al %
mean	666.2	17.8	12	165.0	364.4	146.4	0.82	6.4	6.4	104.8	25.9	81.4	23.9	3.1	12.2	157.9	**4.7**	12.9	26.6	12723	21.7	28.1	1.0
SD	50.6	1.3	2.5	11.4	31.6	10.3	0.42	1.3	2.1	13.8	3.4	30.4	0.1	0.3	1.6	39.4	0.6	1.6	1.1	613.5	0.9	1.3	0.2
min	621.8	16.9	9.2	154.9	334.7	134.7	0.53	5.3	4.7	95.9	22.3	52.8	23.8	2.8	10.5	124.9	4.0	11.2	25.4	12358.0	20.9	26.6	0.9
max	721.3	19.3	14.0	177.3	397.6	154.1	1.31	7.8	8.8	120.7	28.9	113.4	24.0	3.4	13.6	201.5	5.3	14.4	27.6	13431.0	22.6	28.9	1.2
2	Ca	Co	Fe %	K	Mg	Na	Ag	Sn	As	Cu	B	Zn	Sr	Mo	V	Ti	Cd	Cr	Pb	Mn	Li	Ni	Al %
mean	829.8	32.6	23	348.0	989.8	174.9	1.62	12.5	**18.3**	194.9	45.3	149.9	46.8	5.9	27.2	312.9	**8.5**	27.9	48.7	23089	46.2	**51.3**	2.2
SD	43.5	0.2	3.6	20.8	99.9	27.4	0.09	1.9	5.4	23.3	8.4	20.1	2.2	0.6	5.2	74.0	1.5	5.6	2.9	1536.1	0.2	2.0	0.4
min	794.2	32.3	18.6	324.1	878.6	146.9	1.52	10.4	12.4	173.7	36.3	131.5	44.8	5.2	21.5	229.3	6.9	21.9	45.6	21504.0	45.9	49.0	1.8
max	878.3	32.8	25.1	362.0	1072.0	201.7	1.67	14.1	23.1	219.8	52.9	171.3	49.2	6.5	31.7	370.2	9.8	32.9	51.5	24571.0	46.3	52.6	2.6
3.1	Ca	Co	Fe %	K	Mg	Na	Ag	Sn	As	Cu	B	Zn	Sr	Mo	V	Ti	Cd	Cr	Pb	Mn	Li	Ni	Al %
mean	1308.7	9.0	7	858.8	1273.2	161.8	0.07	7.9	12.5	31.2	15.3	54.8	10.4	3.4	51.7	224.3	2.9	53.6	17.9	1789	6.9	15.5	1.87
SD	61.0	0.3	0.7	33.5	79.6	11.7	0.01	0.1	0.1	1.0	0.7	1.3	0.1	0.1	0.8	10.6	0.1	0.9	0.3	36.6	5.4	0.3	0.05
min	1271.9	8.8	5.9	830.7	1203.1	148.7	0.05	7.8	12.4	30.0	14.6	54.0	10.3	3.3	50.8	212.1	2.8	52.6	17.5	1747.9	0.6	15.2	1.83
max	1379.1	9.4	7.2	895.8	1359.7	171.2	0.08	8.0	12.6	31.8	15.9	56.4	10.5	3.5	52.2	231.3	3.0	54.2	18.1	1817.0	10.1	15.7	1.93
3.2	Ca	Co	Fe %	K	Mg	Na	Ag	Sn	As	Cu	B	Zn	Sr	Mo	V	Ti	Cd	Cr	Pb	Mn	Li	Ni	Al %
mean	909.9	6.4	5	558.1	834.8	149.1	<LD	5.5	9.5	20.4	13.6	36.7	6.7	2.3	35.0	174.7	2.3	39.4	13.5	1384	6.2	11.9	1.2
SD	22.6	0.2	0.5	15.0	81.7	23.0	<LD	0.4	0.6	1.1	0.9	2.3	0.5	0.2	2.0	11.5	0.2	2.5	0.8	43.4	0.6	1.0	0.1
min	890.2	6.2	5.1	548.0	781.3	130.4	<LD	5.1	8.9	19.2	12.7	34.2	6.2	2.2	32.8	167.9	2.1	36.9	12.7	1356.0	5.7	10.9	1.1
max	934.6	6.5	6.1	575.4	928.9	174.7	<LD	5.9	10.1	21.4	14.4	38.8	7.1	2.5	36.8	187.9	2.5	41.8	14.4	1434.4	6.8	12.8	1.3
3.3	Ca	Co	Fe %	K	Mg	Na	Ag	Sn	As	Cu	B	Zn	Sr	Mo	V	Ti	Cd	Cr	Pb	Mn	Li	Ni	Al %
mean	1452.2	10.1	7	1079.2	1532.8	150.0	0.087	8.5	15.2	31.2	14.8	50.6	12.4	3.6	55.2	304.7	2.9	62.5	18.1	1940	10.3	16.1	2.1
SD	45.3	0.6	0.2	47.5	38.5	2.4	0.054	0.5	0.7	0.4	0.7	1.6	0.3	0.1	1.8	9.1	0.1	3.7	0.4	69.9	0.3	0.5	0.1
min	1400.1	9.7	6.4	1044.8	1489.6	147.9	<LD	8.2	14.7	30.7	14.4	49.2	12.0	3.5	53.2	294.6	2.8	58.3	17.7	1878.0	10.0	15.7	2.0
max	1483.0	10.8	6.8	1133.4	1563.5	152.6	0.148	9.1	16.0	31.5	15.6	52.4	12.6	3.7	56.3	312.0	3.0	64.8	18.5	2015.6	10.6	16.7	2.2

Table 4. Certified values for TEL and PEL (µg g-1) according CCEE (2001)

Metal	TEL (µg g^{-1})	PEL (µg g^{-1})
As	5.9	17
Cd	0.6	3.5
Cr	37.3	90
Cu	35.7	197
Ni	18	35.9
Pb	35	91.3
Zn	123	315

Table 5: Uranium Concentrations in the three evaluated sites. Values above NASC certified values indicates contamination.

sites	U (µg g^{-1})	SD
1	14.5	0.9
2	**20.2**	**1.3**
3.1	6.3	0.4
3.2	4.6	0.4
3.3	6.3	0.5
U	**2.70**	**NASC**

Table 6: Radionuclides activities in the three evaluated sites

Sites	Ra-226	Pb-210	Ra-228	Th-228
1	212±22	290±43	28±3	32±4
2	215±22	476±69	50±6	47±4
3.1	60±6	249±37	62±6	67±5
3.2	50±5	212±32	53±6	50±5
3.3	61±6	279±41	60±6	69±8

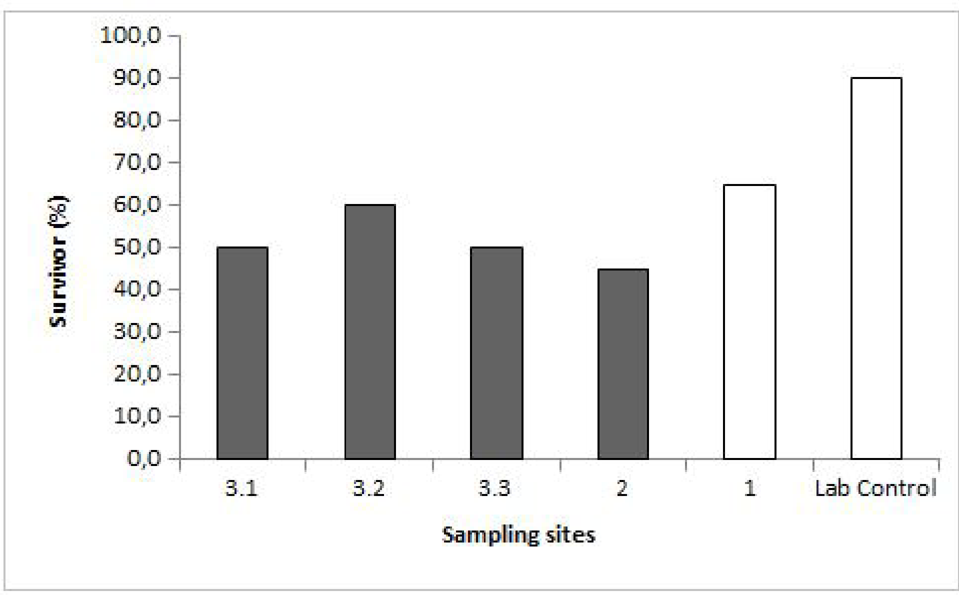

Figure 2. Survivor of *Daphnia similis* after SWI exposures. Numbers indicate the sampling sites (3.1-3.3 are replicates of site 3). Different color indicates statistical differences compared to control results (p<0.05)

DISCUSSION

The Mariana environmental disaster caused commotion and recent publications have reported the toxic effects to biota and marine ecosystems (Bernardino *et al.*, 2019; Gabriel *et al.* 2020a,b). Very recently, results of the criminal report of Betim municipality highlight that the contamination of Mn, Fe, Al, Bo, Sn and As in the Paraopeba river is still a concern for public health (O TEMPO, 2022). In July 2022, the report of Oswaldo Cruz Foundation (FIOCRUZ, 2022) reported that teenagers have been exposed and bioaccumulated As, Mn and Pb.

Therefore, authors have dedicated understanding the obtained results to avoid incorrect or untrue information about Brumadinho's event.

Brumadinho is an important municipality because of regional mining activity. It is located close to the Paraopeba tributary, which is part or the San Francisco river drainage-basin (one of the most important rivers of Brazil). The Paraopeba tributary runs through 21 municipalities (Polignaro and Lemos, 2020). The importance of mining activity along the Paraopeba tributary is historical and started in 1950's decade (Pereira *et al*., 2019). Although population of Brumadinho was small (a total of 40 mi habitants), citizens were dependent of the Vale Company, cultural, social, and economically (Freitas *et al*., 2019). The disrupt of B1 Dam have destroyed the cities infrastructure and local development, not only of mining but also traditional fisheries, agriculture, animal production, ecotourism, and others, all of them dependent of water supply from Paraopeba tributary (Pereira *et al*., 2019, FIOCRUZ, 2019a). Regarding water contamination, the SOS Mata Atlântica (2020) reported that water cannot be consumed due to the high content of metals, such as iron, manganese, copper and chromium, which concentration were above the Brazilian limits.

In relation to the public health, FIOCRUZ (2019b) assumed that it is expected an increment in the incidence of diseases such as yellow fever, schistosomiasis, and diarrheal diseases. In addition, the psychosocial impact of the disaster may aggravate chronic diseases, especially hypertension, diabetes, and kidney failure, and increase the occurrence of mental disorders, such as depression and anxiety.

Regarding the main concern of this event, the increase of metal concentrations, few reports are available. Seven days after the dam rupture, Lourenço *et al.* (2020) have reported Zn, Cu, Fe and Pb concentrations in sediment samples very similar to those obtained in this study, even using a strong acid extraction ($HF+HCLO_4$).

Results obtained by Vergilio *et al*. (2020) for Fe (264.9 mg/g), Al (10.8mg/g), Mn (4.78mg/g), Cd (30.94µg/g), Pb (14.64µg/g), As (4.69µg/g), Sn (547.4µg/g) for the tailing release were different from those obtained in this study. However, all the metals identified in this previous study were found here, and at relevant concentrations. Although this study reports Cd, Zn, Pb, Fe, Mn, Cd concentrations higher than those reported by Parente *et al*. (2021) in sediment samples, authors still found concentrations of concern to biota and public health after one year of the dan rupture. Studying metal speciation in sediment of Brumadinho, Teramoto *et al.* (2021) reported that higher concentrations of Fe and Mn indicated a possible association with the impact of mine tailings and Mn is more likely to be released into the river water.

For ecotoxicological assays, Lourenço *et al.* (2020) did not observe high survivor of *D. similis* exposed to samples collected close to Dam, corroborating to the obtained results of this study. In both cases, an increase of metals considering Brazilian and International guides were observed, confirming availability of metals at concentrations that can cause effects to biota.

It is important to highlight the concentrations of total U, mainly the result obtained closer to Pataxó Solo Sagrado. Vergilio *et al.* (2020) also found U in tailing releases, but in higher concentration ([U] =1457.4µg/g) than those found in the present study. Although no important radioactivity was identified in this study, a contamination of U deserves attention, mainly regarding the source of this metal to the environment.

Besides the effect to biota, metals can cause many effects to human by the movement of and direct contact to the bottom sediment. Regarding Pereira (2019), the silting up of the bottom is a real concern, effecting the Paraopeba river basis.

CONCLUSION

The obtained results ensure that impacts along the Paraopeba river basis could be observed just after 5 days of the Dam rupture. The absence of acute effects after SWI exposure using sediments of site 1 requires further assessments for a proper evaluation of ecological risks, since sublethal responses, and effects at population and community levels were documented following the event. Results support concerns regarding environmental recovery confirming that monitoring of biota, abiotic and physical-chemical parameters should be performed continually.

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AUTHORS CONTRIBUTIONS

Isabella C. Bordon: Project administration, Conceptualization, Funding acquisition, Writing (original draft), Supervision.

Mariana Lima: Data curation, Research, Writing - original draft, Formal analysis.

Deborah I.T. Favaro: Methodology, lab support, Data curation, Research, Investigation, Formal analysis.

Marycel E. B. Cotrim: Methodology, lab support, Data curation, Research, Investigation, Formal analysis.

João C. Ulrich: lab support, Research, Investigation.

Paulo S. C. da Silva: lab support, Research, Investigation.

Camila K. Takahashi: methodology (sampling), lab support, Research, Investigation, formal analysis.

Denis Moledo de Souza Abessa: Ecotoxicology assays, Writing - original draft, laboratory support, Writing (revision and editing).

José Roberto Machado Cunha da Silva: Formal analysis, Writing (revision and editing), Supervision.

COMPETING INTERESTS

The authors declare no conflicts of interest.

CONSENT TO PARTICIPATE AND TO PUBLISH

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Thus, authors confirm their participation in this work and consent the publication of this paper.

ETHICAL STATEMENT

All applicable international, national, and/or institutional guidelines for the care and use of animals were followed

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AVAILABILITY OF DATA AND MATERIALS

The content of this paper reports the original work developed and performed by the forementioned authors. The preprint is available at SSRN: https://ssrn.com/abstract=4047544 or http://dx.doi.org/10.2139/ssrn.4047544

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