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Monitoring deposition and resuspension of the iron ore tailings in the Doce River after the Fundão Dam rupture

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ABSTRACT

The Doce River, located in Southeast Brazil, is of great importance in supplying water for urban use, agriculture, fishing and other purposes. It was affected by a disaster that occurred on November 5, 2015 due to the collapse of the Fundão ore tailing dam, in the municipality of Mariana (MG). This disaster generated socio-environmental consequences, as some regions were severely affected due to the waste released in the river, which was considered potentially toxic in the short to long term. This work presents a temporal analysis of images from the Landsat 8 satellite, associating the aspects of rainfall in dry and rainy months, in years before and after the disaster (2014, 2015, 2016, and 2020), together with the Normalized Difference Water Index (NDWI) obtained by image digital processing, to analyze the relation between dry and rainy periods and the spectral response of images. This analysis allowed the understanding of the behavior of the suspended materials, before and after the disaster, to unravel how the dispersion of tailings occurs. Part of the ore tailing that was deposited along the river went into suspension again in the rainy season one year after the disaster and, five years after, the satellite images show no difference compared to pre-disaster conditions. But, seven years after the spill, there are still iron ore tailings deposited and mixed with the river sediments. The fluvial dynamics are incorporating the tailings into the sediments, originating conducive places to provide various types of metals adhered to the particulate matter.

Keywords: iron ore tailings, rainfall, remote sensing.

Monitoramento da deposição e ressuspensão de rejeitos de minério de ferro no Rio Doce após o rompimento da barragem de Fundão

RESUMO

O Rio Doce, localizado no Sudeste do Brasil, é de grande importância no abastecimento de água para uso urbano, agricultura, pesca e outros fins. Foi afetado por um desastre ocorrido em 5 de novembro de 2015 devido ao rompimento da barragem de rejeitos de minério de Fundão, no município de Mariana (MG). Este desastre gerou consequências socioambientais, pois algumas regiões foram severamente afetadas devido aos rejeitos lançados no rio, considerados potencialmente tóxicos a curto e longo prazo. Este trabalho apresenta uma análise temporal de imagens do satélite Landsat 8, associando os aspectos da precipitação em meses secos e chuvosos, em anos anteriores e posteriores ao desastre (2014, 2015, 2016 e 2020), juntamente com o Índice de Diferença Normalizada de Água (NDWI) obtido por processamento digital de imagens, para analisar a relação entre períodos secos e chuvosos e a resposta espectral das imagens. Esta análise permitiu compreender o comportamento dos materiais em suspensão, antes e após o desastre, para desvendar como ocorre a dispersão dos rejeitos. Parte do rejeito de minério que foi depositado ao longo do rio entrou em suspensão novamente na estação chuvosa um ano após o desastre e, cinco anos depois, as imagens de satélite não mostram nenhuma diferença em comparação às condições pré-desastre. Mas, sete anos após o vazamento, ainda há rejeitos de minério de ferro depositados e misturados aos sedimentos do rio. A dinâmica fluvial está incorporando os rejeitos aos sedimentos, originando locais propícios para fornecer vários tipos de metais aderidos ao material particulado.

Palavras-chave: precipitação, resíduos de minério de ferro, sensoriamento remoto.

1. INTRODUCTION

Several studies sought to measure the environmental damage and future risks linked to the release of iron ore tailings in the Doce River after the collapse of the Fundão (MG) dam operated by Samarco. The disaster occurred on November 5, 2015, when about 50 million cubic meters of mud from mining activities were released into the Doce River Basin (Segura *et al.*, 2016; Carmo *et al.*, 2017) and traveled more than 600 km along the river channel until it reached the Atlantic Ocean (Marta-Almeida *et al.*, 2016; Miranda and Marques, 2016). Some studies have shown immediate impacts as well as inferred long- and medium-term changes in the physical and biotic environment (Queiroz *et al.*, 2018; Vergílio *et al.*, 2021; Duarte *et al.*, 2023), while others have detected the presence of various sources of pollutants that compound the damage caused by the mud (Abessa *et al.*, 2023; Aguiar *et al.*, 2023; Yamamoto *et al.*, 2023; Duarte *et al.*, 2021). Geoprocessing techniques were used to dimension the areas impacted by the disaster (Aires *et al.*, 2018), to analyze changes in the Doce River turbidity (Rudorff *et al.*, 2018), and to evaluate changes in underwater light field (Coimbra *et al.*, 2019) as well as the concentration of sediments in suspension in continental (Aires *et al.*, 2022) and oceanic areas (Marta-Almeida *et al.*, 2016).

The great advantage of using orbital images in this type of study is obtaining indirect measurements of parameters indicative of environmental quality, which allows the evaluation of past conditions in addition to temporal comparisons with the present. This can answer questions related to the dissipation of particulate matter in the environment, either by river transport of the finer particles or by the decantation of remaining fractions. This study aims to contribute in this way, comparing scenarios before and after the collapse of Fundão iron ore dam, by the digital processing of satellite images that recorded events of drought and rain in a stretch of the Doce River near its mouth, in the municipality of Linhares, State of Espírito Santo (Figure 1).

Landsat 8 images were used, with the application of the Normalized Difference Water Index (NDWI) to indirectly monitor changes in the content of particulate matter suspended in water. Direct analyses of the chemical composition of alluvial sediments and iron ore residue deposited in the floodplain after the disaster were also carried out.

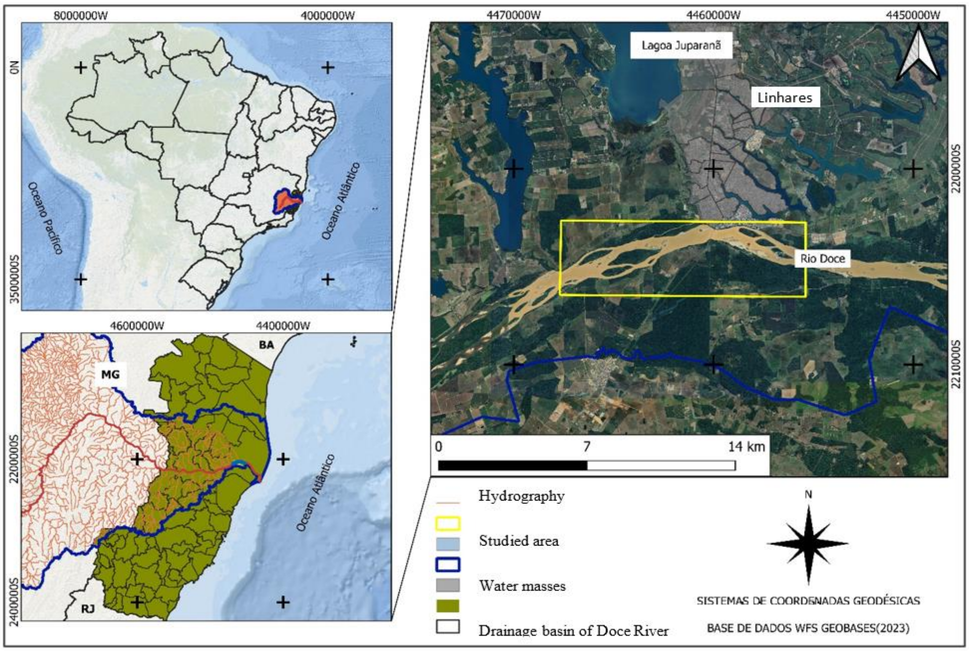

Figure 1. Location of the study area in the municipality of Linhares, State of Espírito Santo, and in the drainage basin of the Doce River lower bank.

2. MATERIALS AND METHODS

2.1. Obtaining rainfall data and orbital images

Rainfall data for the period from 2010 to 2020 (Figure 2) were obtained from the records of the Linhares rainfall station (A614), available by the National Institute of Meteorology – INMET (2023). The rainfall pattern in the region is typical of a tropical climate with a dry winter (Aw in the Köppen Classification) (Alvares *et al.*, 2013). Monthly averages over a 10-year period show rainy months from October to March and dry months between April and September. The year of 2015, when the Fundão Dam collapsed in Mariana (MG), had an anomalously low rainfall pattern between September and December, compared to the monthly averages for the 10-year period. These data were important for choosing the images to be analyzed, aiming to compare the spectral response of the river water in moments before and after the Mariana disaster.

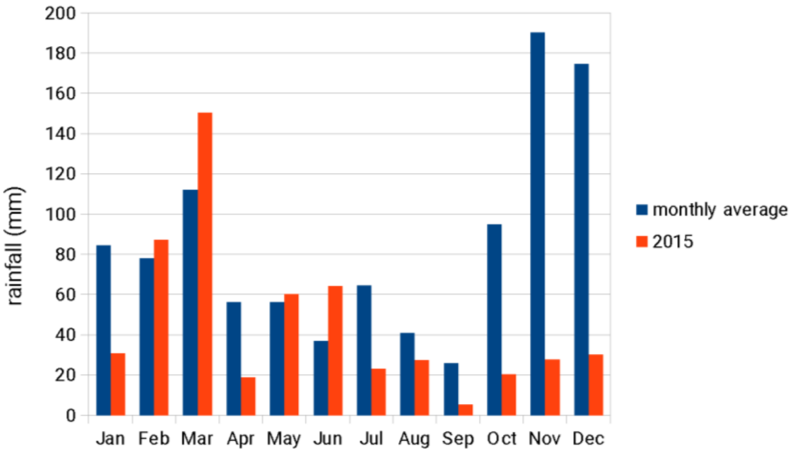

Figure 2. Average monthly precipitation over a 10-year period (2010 to 2020) and throughout 2015, the year in which the Mariana disaster occurred. Data from the rainfall station of Linhares (ES). Data.
Source: National Institute of Meteorology (INMET, 2023).

The orbital images were selected for the most and least rainy months (Table 1), before and after the Mariana disaster, always seeking the lowest possible cloud cover. The arrival of the tailings from the Fundão Dam (MG) in the municipality of Linhares (ES) occurred at the end of November 2015, during a period of drought, which is why images referring to dry months before and after the disaster were selected. The most recent images, from 2020 and 2021, were selected to assess the Doce River current situation, up to six years after the disaster. Precipitation values for the month prior to the date of image acquisition were obtained. For example, if the image corresponds to 11/27/2014, the precipitation interval refers to the total accumulated since 10/27/2014.

Table 1. Date of the Landsat 8 satellite images selected for analysis and the rainfall recorded in the month prior to the date of imaging.

PERIOD	DATE OF IMAGE	MONTHLY PRECIPITATION (mm)
Before the disaster	11/27/2014	206.4
	04/20/2015	17.2
	10/13/2015	20.4
After the disaster	11/30/2015	31.0
	04/22/2016	23.2
	12/18/2016	122.4
After the disaster	06/04/2020	46.6
	12/13/2020	89.8
After the disaster	05/22/2021	7.8
	12/16/2021	193.4

The collection of satellite imagery used is the Landsat 8 Collection 1 Tier 1 calibrated top-of-atmosphere (TOA) reflectance, which has atmospheric correction. Atmospheric correction is widely used for temporal analyses, as it corrects the solar zenith angles according to the time difference between data acquisitions, as well as TOA reflectance, which compensates for the different values of atmospheric solar irradiance derived from the differences between the spectral bands (Chander *et al.*, 2009).

To select images in relation to the rainfall stations positioning, scenes from Orbit 215 and Point 73 were obtained. The scenes were selected based on specific dates, seeking to involve periods of high and low monthly precipitation.

2.2. Normalized Difference Water Index (NDWI) calculation

NDWI, defined by McFeeters (1996) to delineate the features of an aquatic environment, uses reflected near-infrared radiation and visible green light to enhance the presence of such features while eliminating the influence of soil and terrestrial vegetation. The author suggests that the index can be used as a tool in the study of issues related to water quality, particularly regarding turbidity, by remote sensing. The NDWI is calculated with Equation 1.

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)} \quad (1)$$

In which:

Green = Band 3

NIR = Band 5

When Equation 1 is used to process a multispectral satellite image, the bodies of water have positive values; while soil and terrestrial vegetation have zero or negative values, because they typically have higher reflectance than green light (Mcfeeters, 1996).

After calculating the NDWI, the QGis program Version 3.16.5 was used to obtain the means of the index values, limited only to the river environment, according to the maximum and minimum values, considering -1 as the minimum value and 1 as the maximum value. Numerical data were enhanced with the attribution of false color to highlight the observation objects, and other tools such as image contrast and gamma were used to improve the data analysis.

2.3. Collection and analysis of residue and sediment samples

Three field campaigns were carried out to collect samples. As the authors were already researching the sediments of Doce River sandbars in the studied area, the first collection was carried out before the disaster, in 2014. After the disaster, in 2016, the second collection was carried out and the third collection was carried out in 2022. In these campaigns, alluvial sediments (SED-A) (Figure 3a) were collected, iron ore residues deposited by the mudflow (RES) (Figure 3b), and in 2016 and 2022 also sediments in which a mixture with the disaster residue was observed (SED-D1 and SED-D2) (Figure 3c). In all campaigns, four samples of the same type were collected, composing replications. The samples were analyzed by X-ray fluorescence spectrometry (XRF) to quantify the contents of the essential chemical elements, expressed in percentages of oxides: SiO_2, Al_2O_3, Fe_2O_3, CaO, K_2O, TiO_2, MnO, and ZrO_2.

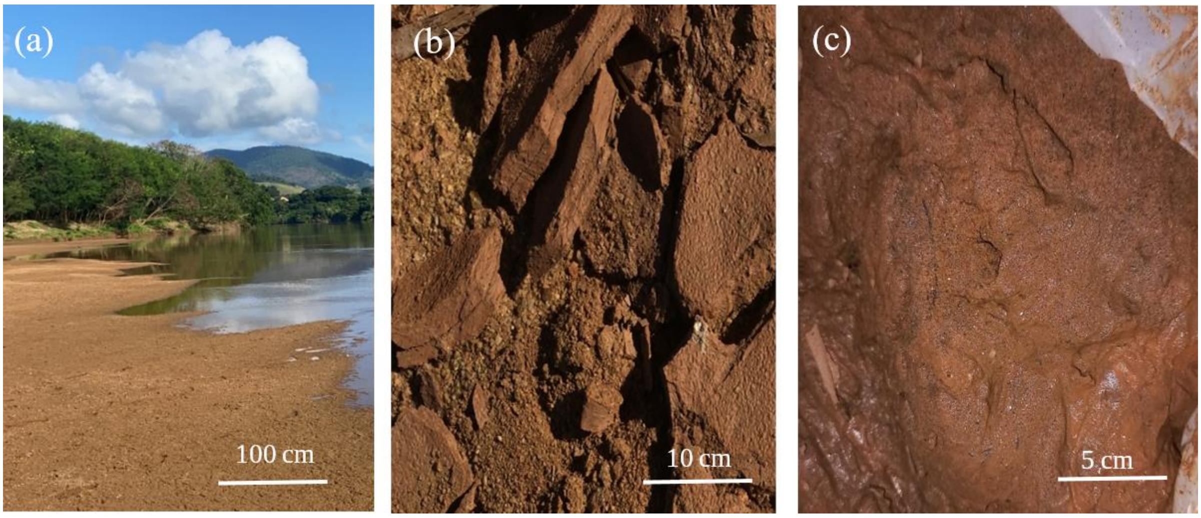

Figure 3. (a) Sample collection site on the Doce River banks, where (b) layers of iron ore residue and (c) sandy sediments mixed with the residue were deposited.

3. RESULTS

3.1. Aerial images and NDWI in a stretch of the Doce River near Linhares (ES)

Figure 4 shows satellite images of the region of Linhares (ES) in false-color composition (left column) and the Normalized Difference Water Index (NDWI) calculated for the same area (right column), including periods of rain and drought (as shown in Table 1), before and after the Mariana disaster, on 11/05/2015.

In the image of 11/27/2014, referring to a rainy season, the Doce River appears in navy blue, while the riverside areas and sand bars are in green. The NDWI calculated for this same stretch shows the river channel in a reddish tone and the river banks and sand bars in green. The images of 04/20/2015 and 10/13/2015, preceding the disaster, correspond to months with low rainfall, in which the river reflects, in false color, a dark blue tone tending to black and the NDWI levels remain similar to the rainy season.

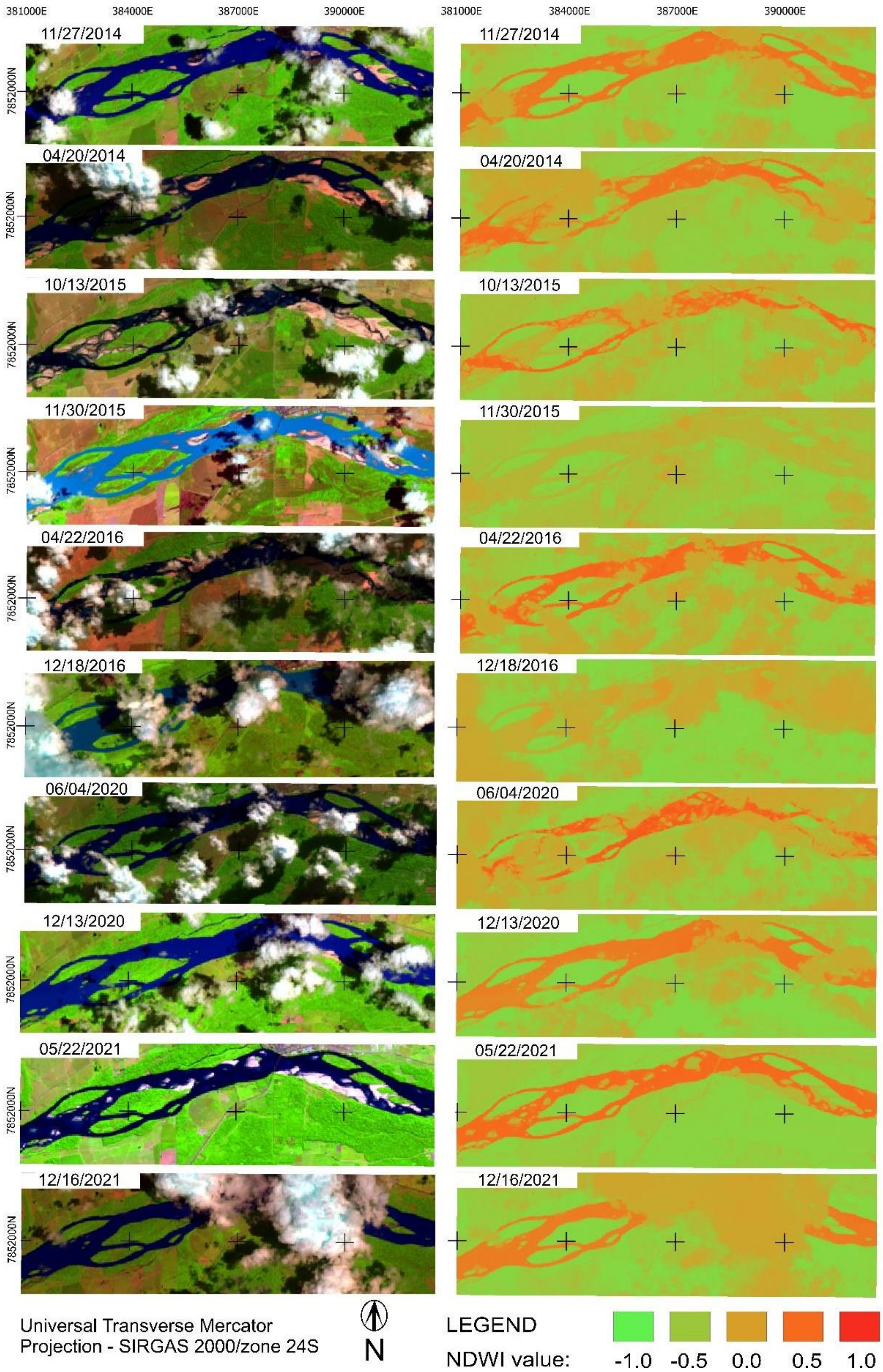

Figure 4. Landsat 8 images and NDWI of the studied area, in months of rain and drought, before and after the collapse of the Fundão Dam (MG). The environmental disaster occurred on 11/05/2015.

In the image from 11/30/2015, which is from 25 days after the Fundão Dam collapse, the river channel reflects a light blue color and the NDWI is considerably altered, with negative values similar to those of dry places, external to the river channel. This is due to the load of particulate matter that invaded the river with the arrival of the mud from mining activities.

In the next image (04/22/2016), in a low rainfall month after the disaster, the NDWI's river returns to previous patterns, indicating the transport of the mud to the ocean and/or sedimentation of the particulate matter in the bottom. However, almost a year after the dam collapse (12/18/2016), with the arrival of a rainy season (although with less precipitation than in the 2014 rainy season), the river exhibits a similar pattern to that observed in the month of the disaster, indicating the resuspension of the sedimentary load in the water column. As of 2020, both in times of drought and in times of rain, the NDWI pattern is similar to that before the disaster. Thus, the rainy months of 2014 (before the disaster) and 2021 (six years after the disaster) have very close NDWI values, showing no further remobilization of particulate matter as significantly as observed in 2016, even in the rainy season.

Figure 5 shows the relation between rainfall and the average NDWI in the Doce River course in the moments before and after the collapse of the Fundão Dam. Under normal conditions, the average NDWI recorded in this stretch of the river ranged from -0.036 to 0.012 (range highlighted in Figure 5 by the dashed green lines). Corroborating the images, there are two moments in which the NDWI values are more negative: in November 2015 (NDWI of -0.11) and in December 2016 (NDWI of -0.07). The first is due to the mud release into the river and the second due to the remobilization that occurred in the rainy month after the disaster. The next record in a rainy month was in 2021, when the NDWI became similar to the values before the disaster, in the rainy month of 2014.

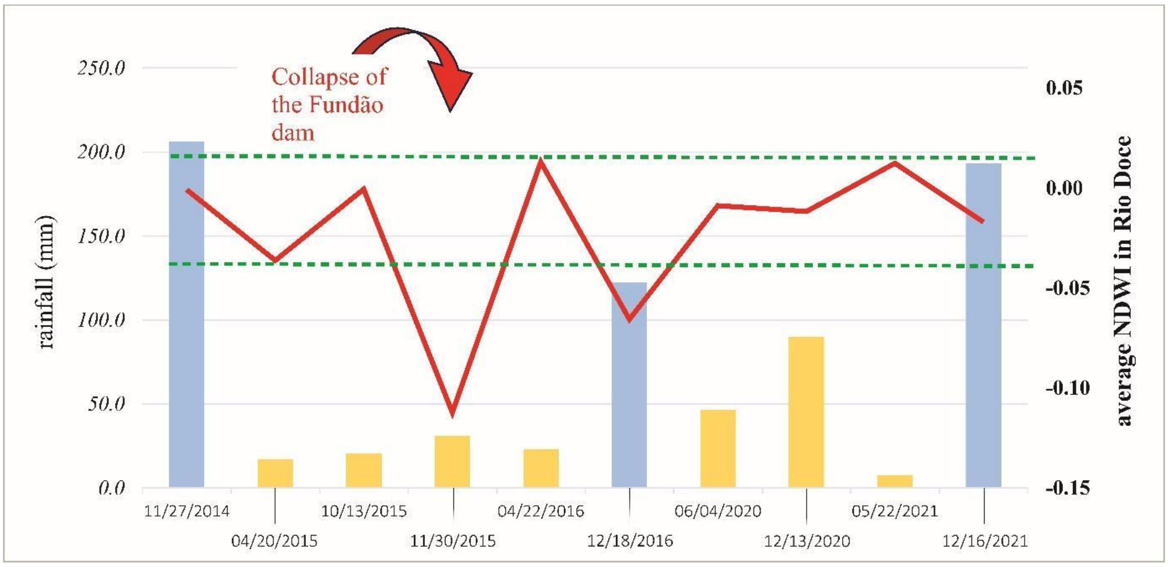

Figure 5. Variation of NDWI (red line) in the Doce River stretch near Linhares (ES) and rainfall in the rainy months (blue bars) and dry months (yellow bars), before and after the Fundão Dam collapse, on 11/05/2015. The dashed green lines indicate the NDWI range of river normal conditions.

3.2. Chemical composition of residues and sediments

The residues and sediments of the Doce River contain Si, Al, and Fe, which account for over 90% of their total chemical composition (Table 2). The other detected constituents (K_2O, CaO, TiO_2, MnO, and ZrO_2) are secondary or traces. Regarding the main constituents, when observing the average the residues present the relative proportion of Fe > Al > Si, unlike the sediments, in which the ratio is Si > Al > Fe (Figure 6). The sediments collected on the two dates after the dam collapse, in 2016 and 2022, show increased proportions of Al and Fe over the years. This indicates the sedimentation of the residue next to the river sandbars and the mixing of mining particles, richer in Fe and Al, with the original sediments.

Table 2. Main chemical composition of the iron ore residue (RES) deposited in the Doce River alluvial plain in the region of Linhares (ES) and of the sediments collected before (SED-A) and after the collapse of the Fundão Dam, in 2016 (SED-D1) and in 2022 (SED-D2).

SAMPLE	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	TiO_2	MnO	ZrO_2
RES	28.48	30.80	36.04	1.96	0.40	1.26	0.33	0.14
	24.35	28.27	43.49	1.32	0.47	1.11	0.46	0.03
	24.43	34.29	37.73	1.40	0.27	0.97	0.39	0.03
	26.95	30.18	38.61	1.87	0.29	1.17	0.32	0.08
SED-A	70.27	14.68	7.40	4.59	0.88	0.70	0.19	0.14
	60.36	0.03	25.16	5.59	1.79	3.31	0.30	1.23
	66.16	19.86	7.70	3.89	0.83	0.88	0.13	0.19
	70.71	13.73	5.49	3.26	0.66	0.78	0.08	0.13
SED-D1	41.67	29.19	22.18	2.88	0.50	1.95	0.10	0.60
	75.95	12.39	5.10	4.07	0.71	0.35	0.00	0.10
	67.16	17.42	8.64	4.16	0.69	0.65	0.14	0.13
	30.54	26.67	32.82	4.09	0.67	2.79	0.26	0.71
SED-D2	49.73	33.28	12.90	1.10	0.30	1.78	0.06	0.13
	39.10	25.39	33.02	1.15	0.33	1.86	0.07	0.13
	43.96	35.08	18.65	1.15	0.29	1.81	0.06	0.13
	38.90	23.94	33.26	0.88	0.29	1.81	0.05	0.12

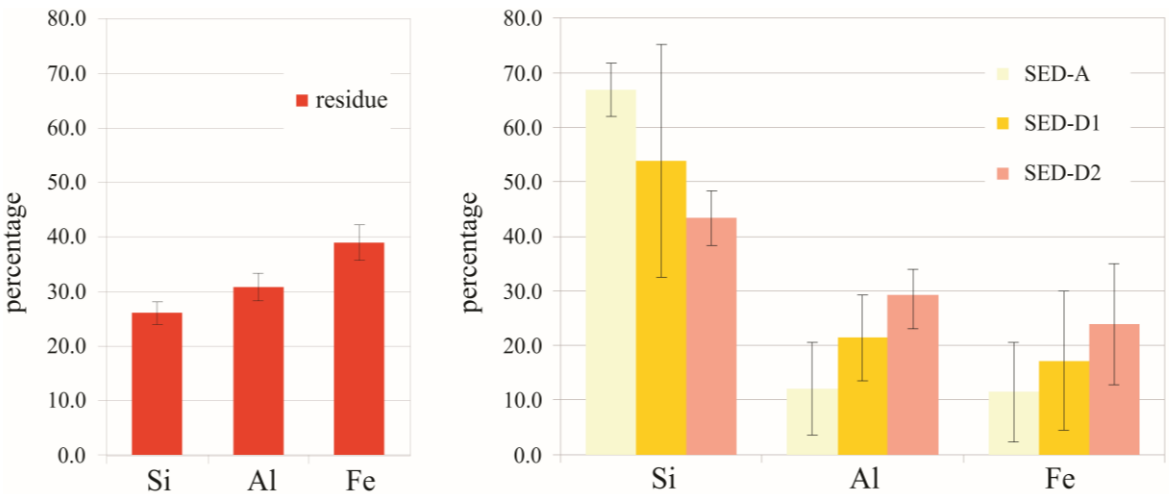

Figure 6. Main chemical composition of (a) the iron ore residue deposited on the Doce River alluvial plain and (b) the alluvial sediments collected before (SED-A) and after the disaster, in 2016 (SED-D1) and in 2022 (SED-D2).

4. DISCUSSION

The presented data, using Landsat 8 images and the Normalized Difference Water Index (NDWI), show how the iron ore residue altered, at certain moments, the turbidity pattern of the Doce River near Linhares (ES), about 200 km far from the site of the Fundão Dam collapse (Mariana, MG). According to Rudorff *et al.* (2018), the arrival of mud from mining activities at the Doce River mouth raised the water turbidity to levels above 1000 NTU after the disaster, and Resolution 357/2005 of the National Environment Council (CONAMA) determines a maximum value of 100 NTU (CONAMA, 2005). According to those authors and the rainfall data from this study, the years following the disaster were drier than usual, which must have contributed to the deposition and permanence of part of the mining residue on the river sediments.

The residue deposited in the Doce River and its banks went into suspension again during rainy events in the months following the disaster, as evidenced in the NDWI of the 2016 rainy month. The resuspension of mud from mining activities in the water column of the Doce River has already been reported in previous studies (e.g. Coimbra *et al.*, 2019). Rudorff *et al.* (2018) observed that the mud from Fundão Dam deposited on the Atlantic coastal margin remained as a source of resuspension of fine sediments to the ocean during the years of 2016 and 2017. Corroborating this study data, Santos *et al.* (2021) point out that, although the spectral response of river waters has become similar to previous conditions about six months after the disaster, after a year, in the first prominent rain event, the material returns to suspension. The resuspension is also reported by Aires *et al.* (2022), which used remote sensing data up to 2020.

Sediments are predominantly sand-sized grains, while iron ore residue is of a silt-clay type (Duarte *et al.*, 2021), which may explain the difference in NDWI right after the disaster and in the rainy month a year after the disaster. After this time, the sedimented fine material was mixed to sandy sediments which no longer allowed the fine sediments resuspension. Therefore, what had altered the turbidity of the river until a year after the disaster was no longer observed in such a prominent way.

After six years, the residue resuspension in the river water is no longer observed through satellite images at levels similar to those of 2015 and 2016, even in the rainy seasons. However, it should be noted that the particulate matter from the Fundão Dam remained in the continental area at least until 2022, that is, seven years after the disaster, when we carried out the second field campaign. The bulk composition of the residue studied here is similar to that presented by other authors (e.g. Sá *et al.*, 2023), with predominance of Si, Al, and Fe. Although the trace metals play the main role in potential environmental impacts, Al and Fe can also harmful water and soil quality in specific situations (Duarte *et al.*, 2023). Another worrying component is Mn, which, although in low concentration in mass composition, as presented here, it can be released to the environment, as observed by other works performed in the estuary (Queiroz *et al.*, 2021) and inland (Santos *et al.*, 2021) of the Doce River Catchment. Although major influence of iron ore residue on river turbidity is no longer expected, it is important to pay attention to the riparian zones along the Doce River, which can be storage sites for fine particulate matter. The fluvial depositional environment works by selecting the grains and depositing the finest materials in low-energy locations, such as wetlands and marginal swamps (Miall, 2006). These sites also tend to accumulate organic matter that, associated with minerals from mining activities, can concentrate potentially toxic and/or dangerous metals. Santos *et al.* (2023) carried out tests on sediments of the Gualaxo do Norte River (MG), one of the tributaries of the Doce River located in an area affected by the disaster. The study showed that both simple and complex organic matter can cause solubilization of Fe, Mn, Ba, Al, Zn, and other trace elements and that indigenous, heterotrophic, and anaerobic microorganisms act as catalysts in the process. The excess of organic matter released by untreated urban sewage is also a reagent, and its participation in this process can be relevant. Other authors also found worrying levels of dangerous metals in residue and sediments deposited in the Rio Doce alluvial plain, such as As and Cd (e.g. Duarte *et al.*, 2021), including some that occur above the acceptable value for carcinogenic risk, such as As, Cr, and Ni (Camêlo *et al.*, 2024).

It is worth noting that before the Fundão Dam collapse, the water quality of the Doce River was already altered by multiple sources of contamination (Dias *et al.*, 2018), particularly the discharge of industrial and domestic effluents and mining waste into the upper and middle reaches of the river. Thus, the feedback presented in this study, although showing attenuation of the impacts of the Mariana disaster on river water turbidity according to NDWI data, does not necessarily indicate that current water quality conditions are adequate.

5. CONCLUSIONS

The comparison of conditions of the Doce River in the stretch of Linhares (ES) using the Normalized Difference Water Index (NDWI) after the collapse of the Fundão Dam in Mariana (MG) shows that the arrival of mud from mining activities in 2015 significantly altered the turbidity of the water. Part of the particulate matter that was deposited along the river system went into suspension again in the rainy season of 2016, that is, one year after the disaster. In 2020, five years after the disaster, the reflectance of river water captured by satellite imagery returned to be similar to the pre-disaster pattern.. On the other hand, seven years after the spill, there is still mud from mining activities deposited and mixed with the river sediments. The fluvial dynamics are incorporating the iron ore tailings into the sediments, mainly in sites with low energy of water that can favor the liberation of hazardous metals by the ore tailing.

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