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Spatial and temporal analysis of the collapse of the tailings dam in Brumadinho, Brazil

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Abstract

Mining is an important economic activity in the world. Mining activities are known for their high environmental impacts. Considering the high magnitude of some operations and amounts of tailings produced, the mining activity has represented a risk for several regions and populations, which can be affected by accidents and inefficient disposal and monitoring systems. Remote sensing has been frequently used to map areas that are large or difficult to access; it enables the obtaining of information on objects or phenomena on the Earth's surface without requiring physical contact, making it an important source of data collection that can be used for several purposes. Images used in remote sensing provide a synoptic and multitemporal view of large areas and are an alternative for environmental studies. The objective of this work was to evaluate the extension of the area affected by the collapse of the tailings dam of the Vale S.A. company in the Córrego do Feijão stream mine, in the municipality of Brumadinho, state of Minas Gerais, Brazil, which occurred on January 25, 2019, causing an environmental impact that will last for many years. The dimension of this environmental impact was analyzed using imagery of the Planet's satellite constellation with spatial resolution of 3.0 meters. The methodology used was based on digital image processing, using the *PCI Geomatics* and *ENVI 5.3* software, which made possible the quantification of the affected area. Two different methods were used and the results were compared to those provided by the State Secretariat for Environment and Sustainable Development of Minas Gerais, Brazil. The results showed an affected area of 2.964096 km^2, from the Brumadinho dam to the Paraopeba River.

Keywords: Remote Sensing, Ambiental Impact, Digital Image Processing.

Introduction

In the last 50 years, the number of people exposed to disaster risks has been increasing in the world faster than their capacity to decrease such vulnerability, resulting in intense and extensive (time and space) environmental impacts (FREITAS et al., 2016).

The Resolution no. 01/86 of January 23, 1986 (BRASIL, 1986) established by the Brazilian National Council for Environment (CONAMA), in its article 1, defines environmental impact as any changes in physical, chemical, or biological properties of an environment, caused by any

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form of matter or energy resulted from human activities that, direct or indirectly, affect the health, safety, or well-being of a population; social and economic activities; and biota and quality of environmental resources.

Mining is an important economic activity in Brazil that causes high environmental impacts. Considering the high magnitude of some operations and amounts of tailings produced, the mining activity has been a risk for several regions and populations, that can be affected by accidents and inefficient disposal and monitoring systems (BNDES, 2017).

The collapse of the tailings dam in the Córrego do Feijão stream mine, in the municipality of Brumadinho, state of Minas Gerais (MG), Brazil, occurred on January 25, 2019 was one of the most significant mining disasters in Brazil, which resulted in 270 deaths and discharged approximately 11.7 million cubic meters of mining tailings in the environment. The resulting changes denoted serious environmental and socioeconomic impacts due to the volume of accumulated tailings and their toxic potential (PEREIRA et al., 2019).

Considering the magnitude of the disaster and the difficult access to the affected areas, geotechnologies, such as aerial or orbital image analysis, were important to study the spatial dimension of such disaster.

According to Florenzano (2007), remote sensing can be defined as a technology that enables the obtaining of images and other types of data of the Earth's surface by capturing and recording the energy reflected or emitted by it. Remote sensing has been a technique used in environmental studies, since it enables the analysis of large areas without requiring physical contact. This is possible because remote sensing uses satellite imagery to measure the electromagnetic radiation reflected or emitted by targets on the Earth's surface and processes this information in terms that can be interpreted.

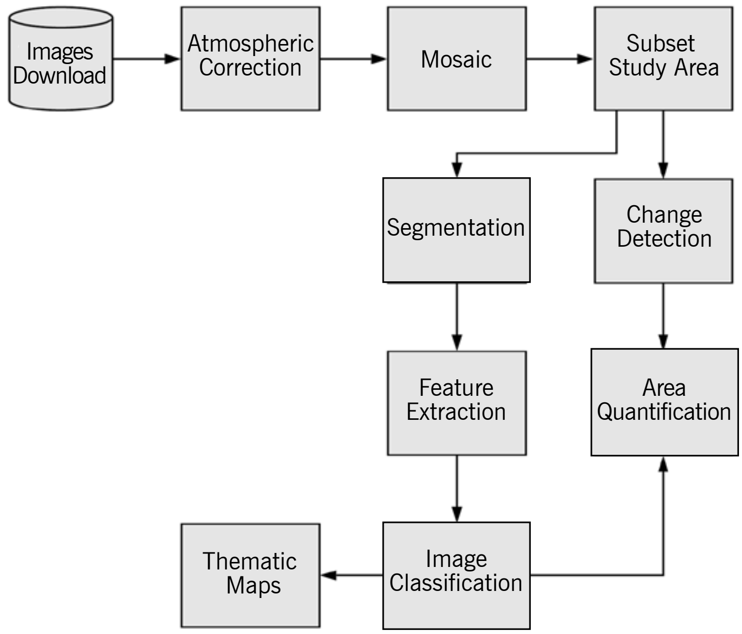
In this context, the number of studies using satellite imagery combined with technical Digital Image Processing (DIP) has been increased, showing the importance of this technique for the analysis of environmental disasters. Silva et al. (2018) conducted spatial and temporal analysis of the environmental disaster occurred in Mariana/MG, Brazil, using DIP.

The objective of this work was to evaluate the area affected by the collapse of the tailings dam in the municipality of Brumadinho/MG, Brazil, through spatial and temporal analysis, using satellite imagery. Such analysis was conducted to quantify the affected area through the change detection by comparing images of the area acquired before and after the occurrence of that environmental disaster.

Material and methods

The spatial and temporal analysis was conducted using imagery from the Planet's satellite constellation, taken in two different times, orthorectified with spatial resolution of 3.0 meters each. The *PCI Geomatics 2018* and *ENVI 5.3* software were used for the digital image processing and the *QGIS 2.14.*8 software was used to develop thematic maps and quantify the affected area. The chosen methodology followed the steps presented in Figure 1.

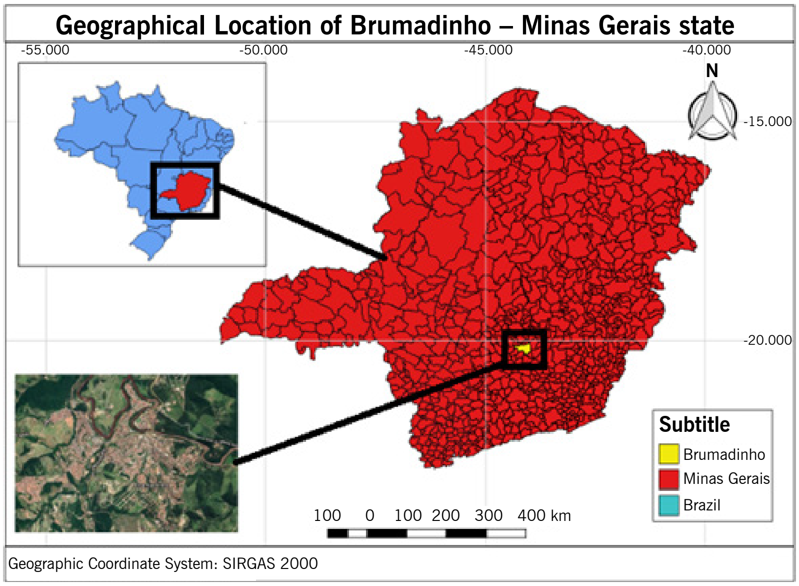
Figure 1 – Steps of the methodology.



Source: Elaborated by the authors (2019).

The first step consisted of acquisition of satellite images of the municipality of Brumadinho/MG, Brazil. The geographical location of the municipality is shown in Figure 2.

Figure 2 – Geographical location of the municipality of Brumadinho/MG, Brazil.



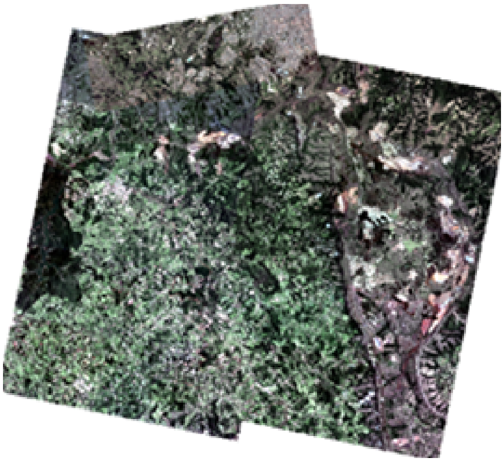
Source: Elaborated by the authors (2019).

The Planet Scope Analytic Basic Scene product consists of multispectral data from the Planet's satellite constellation composed of images from 4 spectral bands (blue, green, red, and near infrared). The images used were from different times: before the disaster (January 22, 2019) and after the disaster (February 01, 2019), at the closest time possible to its occurrence, which was on January 25, 2019.

The second step consisted of atmospheric correction of the images that compose each scene. The images were processed using the ATCOR model in the *PCI Geomatics* 2008 software. Original images were available in radiometric radiance form; they were transformed into surface reflectance after the atmospheric correction procedure. Atmospheric correction was needed to reduce the atmosphere effect on the recorded values of each image. The atmosphere interacts with electromagnetic radiation, causing significant changes in the radiation flow from the target. The main evidences of these effects on the images are the decrease in surface brightness in specific spectral regions and the presence of mist, with loss of sharpness, in regions with lower wavelengths (LATORRE et al., 2002).

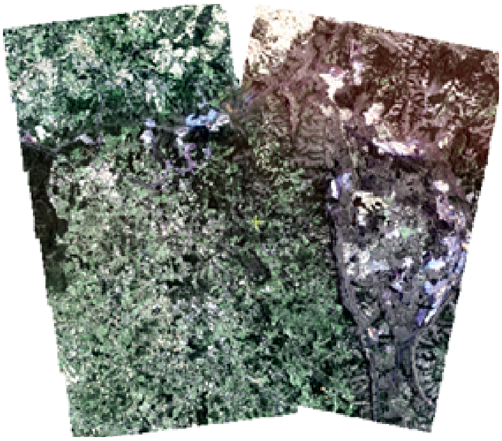
The third step was the production of mosaics referring to each time, which were composed of several images that were put together forming a mosaic, so it was possible to evaluate the area of interest. The mosaics of each time were generated using 3R2G1B color composition, as shown in Figures 3 and 04. They were generated with no normalizations or changes in the pixel values of the images to maintain the integrity of the reflectance recorded by the satellite sensor.

Figure 3 – Mosaic from images referring to January 22, 2019, before the occurrence of the collapse of the tailings dam in Brumadinho/MG, Brazil.



Source: Elaborated by the authors (2019).

Figure 4 – Mosaic of images referring to February 01, 2019, after the occurrence of the collapse of the tailings dam in Brumadinho/MG, Brazil.



Source: Elaborated by the authors (2019).

The fourth step consisted of performing cutouts on the mosaics referring to the affected area by the collapse of the dam in each time.

The fifth step was the detection of changes; According to Singh (1989), the change detection in remote sensing studies consists in identifying alterations in the Earth's surface through satellite images of a same area collected at different times. These changes were detected using the *PCI Geomatics* and *ENVI 5.3* software with the method of image subtraction pixel by pixel. This method subtracts an image from another, highlighting the changes in the land surface cover.

The affected area was quantified using the *QGIS 2.14.8* software, considering the dam area and all affected areas from the dam to the Paraopeba River, disregarding the Paraopeba River, since the images obtained do not include all its extension.

The sixth step was the classification of images, attributing meaning to the pixels by considering their numeric properties. According to Novo (2010), classification techniques are used as a last analysis to attribute a label to each pixel according to its spectral and spatial properties. The supervised classification technique Support Vector Machine (SVM) was used; according to Campbell (1996), can be simply defined as the process in which samples of known identity are used to classify pixels of unknown identity.

Six land use and occupation categories were defined for the supervised classification of the following images: trees, ground vegetation, mining tailings, bare soil, water, and urban area. All identified classes in the scene were inserted in the classification key.

The supervised classification process was carried out in the *PCI Geomatics* software through the following phases:

- image segmentation: according to Vasconcelos and Novo (2004), it is needed to group adjacent and similar pixels, generating homogeneous regions.
- feature extraction: data were extract from the original data, and then attributes, in spectral and geometric forms, were generated.
- determination of classes of interest: trees, ground vegetation, mining tailings, bare soil, water, and urban area.
- collection of representative samples of each class.
- classification of images using the classification algorithm SVM of the PCI Geomatics software.
- evaluation of the quality of the classifications in the *PCI Geomatics* software, using new validation samples that represent each class. The Kappa index method was chosen to perform the evaluation.

According to Congalton (1991), the Kappa index is satisfactory to evaluate the precision of thematic classifications; it considers all confusion matrix in its calculation, including elements outside the main diagonal, which represent disagreements in the classification; it is different than the global accuracy, which uses only diagonal elements (actual agreement).

Chart 1 presents the classification performance levels according to the Kappa indexes obtained.

Chart 1 – Kappa index and corresponding performances of classification.

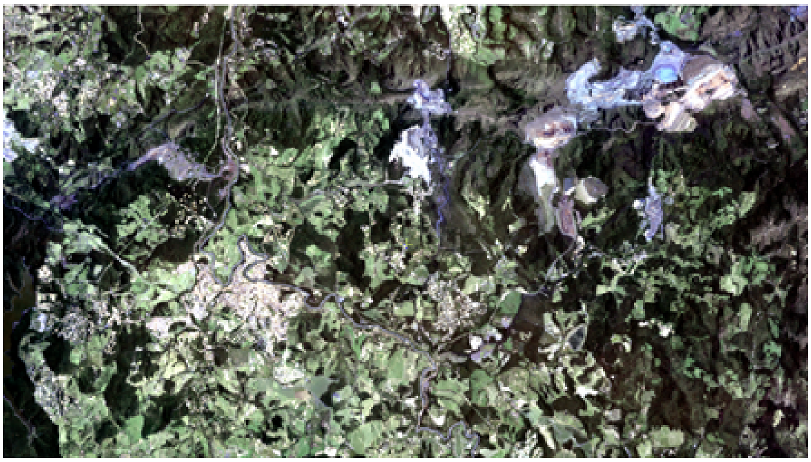
Kappa index	Performance
< 0	Very Bad
0 < k ≤ 0,2	Bad
0,2 < k ≤ 0,4	Reasonable
0,4 < k ≤ 0,6	Good
0,6 < k ≤ 0,8	Very Good
0,8 < k ≤ 1,0	Excellent

Source: Adapted from Landis and Koch (1977).

Results and discussion

The cutouts performed on the mosaics resulted in images for each time, as shown in Figures 5 and 6.

Figure 5 – Cutouts performed on the mosaic composed with images of the study area acquired on January 22, 2019.



Source: Elaborated by the authors.

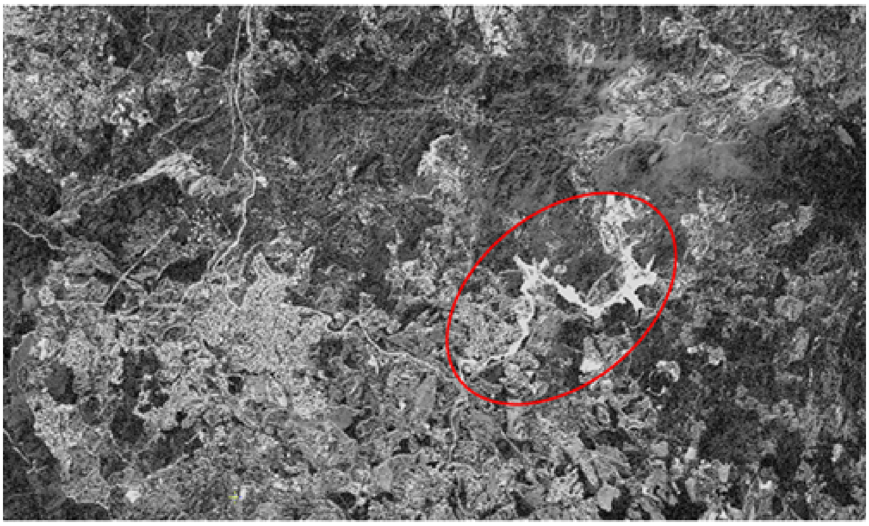
Figure 06 – Cutouts performed on the mosaic composed with images of the study area acquired on February 1st, 2019.

Source: Elaborated by the authors.

The cutouts showed the extension of the area affected after the collapse of the dam, identified by the area marked in red in Figure 6.

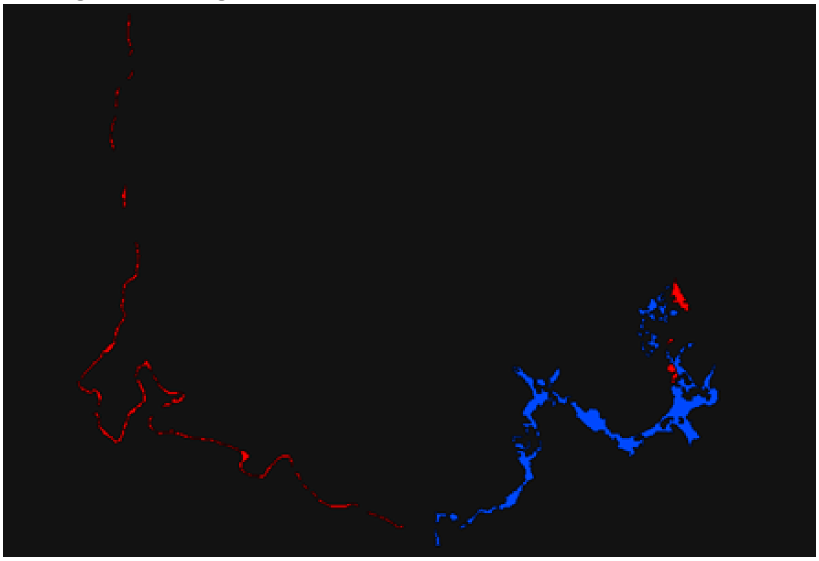
The results of the changes detected by the procedures carried out using the *PCI Geomatics* and *ENVI 5.3* software are shown in Figures 7 and 8:

Figure 7 – Detected changes according to the PCI Geomatics software.



Source: Elaborated by the authors (2019).

Figure 8 – Detected changes according to the ENVI 5.3 software.



Source: Elaborated by the authors (2019).

The area highlighted in white in Figure 7, represents the greatest changes detected by the processing done, and denotes the presence of tailings. The area highlighted in red and blue, in Figure 8 also denotes the presence of tailings. The different colors are explained by differences in land cover before the collapse of the dam: the area represented in red was covered with clear water, and the area in blue was covered with vegetation, constructions, and soil.

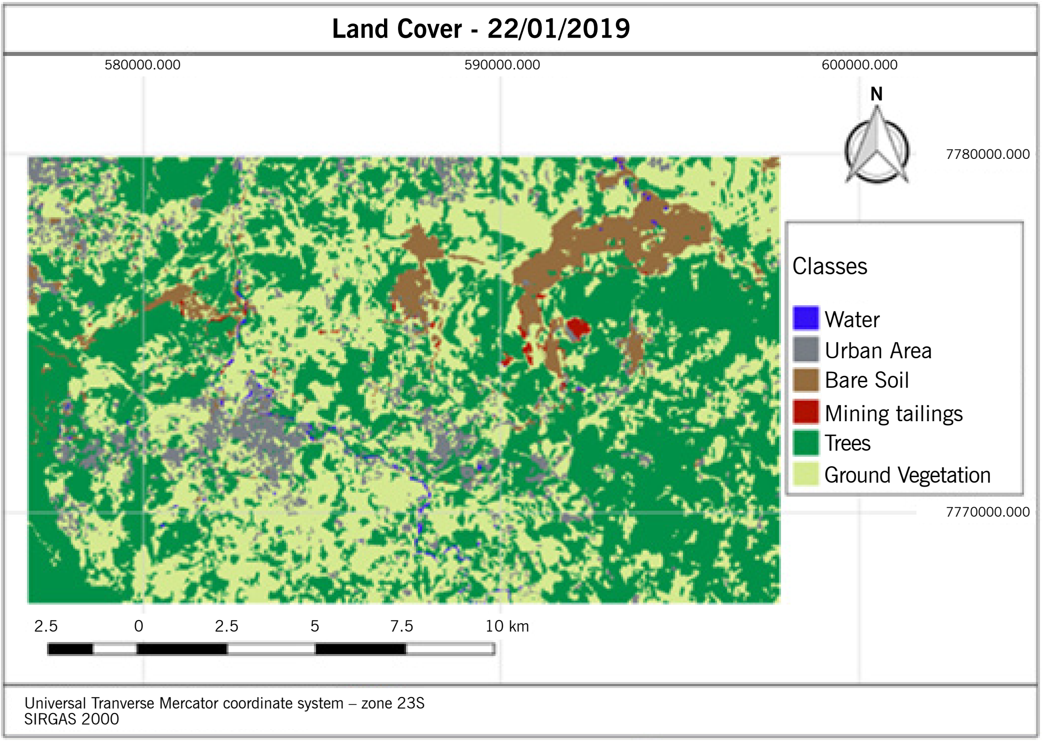
Therefore, Figures 7 and 8 show the changes occurred in the study area after the collapse of the dam. The change detection using the software *ENVI 5.3* enabled the use of thresholds to isolate the affected area, removing small changes from the process to quantify the affected area.

The affected area quantified by the method of change detectionwas 1.64792 km^2 hectares, from the dam to the Paraopeba River.

The method of classification of images was used to develop land cover maps for both times, and for a new quantification of the affected area.

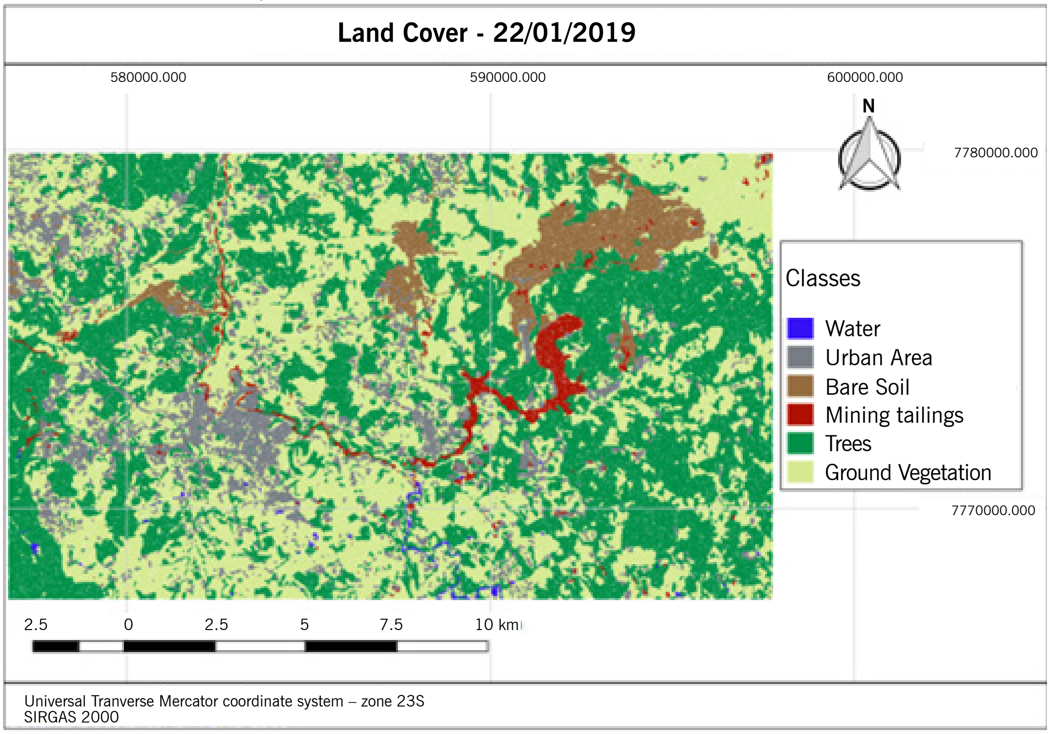
The maps developed by the classification of images, using the PCI Geomatics software, for each time is shown in Figures 9 and 10.

Figure 9 – Land cover map developed by classification of images for the study area before the collapse of the tailings dam in Brumadinho/MG, Brazil.



Source: Elaborated by the authors (2019).

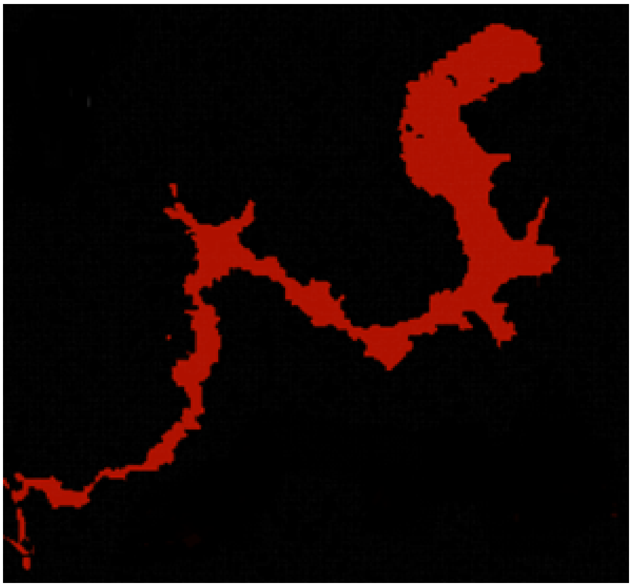
Figure 10 – Land cover map developed by classification of images for the study area after the collapse of the tailings dam in Brumadinho/MG, Brazil.



Source: Elaborated by the authors (2019).

The classification of images using data acquired after the disaster also enabled the quantification of the area affected by the tailings, from the dam to the Paraopeba River. Figure 11 shows the area quantified by the classification of images. The other classes were represented in black only to visually isolate the class Tailings.

Figure 11 – Area affected by the mining tailings, quantified by classification of images.



Source: Elaborated by the authors (2019).

The area quantified by the classification of images (Figure 11) was 2.964096 km², from the dam to the Paraopeba River. The difference between areas found by the classification of images and change detectionwas 1.31618 km². The quantification of the area made by the State Secretariat for Environment and Sustainable Development of Minas Gerais, Brazil (SEMAD) – whose methodology was not disclosed – was used to assess the method that presented more coherent results.

The classification of images of the present study showed similar values to those of the SEMAD's study, showing a total of 2.90 km², considering the area of the dam and all area affected from the dam to the Paraopeba River. The area quantified by the classification of images was more similar to that found by the SEMAD than to that estimated in the step of detection of changes, with a difference of 0,0.4096 km² above those estimated by the SEMAD.

The values obtained by the change detectionpresent divergent results from those published by the SEMAD. This occurred because the change detectionin the ENVI software considers only the main changes.

The quality of the classification of images was assessed in the PCI Geomatics software by analysis of accuracy and calculation of the Kappa index for the two classifications.

Tables 2 and 3 show the distribution of accuracy and Kappa index for each class defined for the images in each time.

Table 2 – Accuracy and Kappa index for each class of land use and occupation defined from satellite images acquired on January 22, 2019, before the collapse of the tailings dam in Brumadinho/MG, Brazil.

Class	Producer accuracy (%)	User accuracy (%)	Kappa index
Bare soil	100.00	90.91	0.89
Urban area	57.14	100.00	1.00
Ground vegetation	87.71	70.59	0.63
Trees	78.95	88.24	0.84
Mining tailings	94.44	89.47	0.86
Water	100.00	100.00	1.00

Source: Elaborated by the authors (2019).

Table 3 – Accuracy and Kappa index for each class of land use and occupation defined from satellite images acquired on February 01, 2019, after the collapse of the tailings dam in Brumadinho/MG, Brazil.

Class	Producer accuracy (%)	User accuracy (%)	Kappa index
Bare soil	100.00	81.82	0.78
Urban area	90.00	100.00	1.00
Ground vegetation	76.92	100.00	1.00
Trees	100.00	92.31	0.90
Mining Tailings	100.00	87.50	0.86
Water	100.00	100.00	1.00

Source: Elaborated by the authors (2019).

The Kappa indexes found for each class showed that the class Ground Vegetation presented the lowest index in the images acquired on January 22, 2019, with a Kappa index of 0.63, which is classified as Very Good; and the class Bare soil was the one that presented the lowest index in the images acquired on February, 01, 2019, , with a Kappa index of 0.78, also considered Very Good, according to Landis and Koch (1977).

Tables 4 and 5 show the total accuracy values and overall Kappa index for the images acquired, respectively, on January 22 and on February 01, 2019.

Table 4 – Accuracy of the classification referring to satellite images acquired on January 22, 2019.

General statistics	Values
Global accuracy	86.11%
Kappa index	0.83

Source: Elaborated by the authors(2019).

Table 5 – Accuracy of the classification referring to satellite images acquired on February 1st, 2019.

General statistics	Values
Global accuracy	92.59%
Kappa index	0.91

Source: Elaborated by the authors (2019).

The validation of results showed that both classifications had Excellent performance, according to Landis and Koch (1977), since they showed Kappa indexes higher than 0.8.

Conclusion

The digital processing of images made it possible to evaluate the extension of the area affected by the collapse of the tailings dam of the Vale S.A. company, in the Córrego do Feijão stream mine, municipality of Brumadinho, state of Minas Gerais, Brazil, which occurred on January 25, 2019, showing the high significance of the changes in land cover, from the dam to the Paraopeba River.

The area affected by the disaster, from the dam to the Paraopeba River, was quantified by change detection and classification of images, and; the classification of images had higher precision than previous studies. The area quantified by the change detectionshowed no good precision, which is explained by the inclusion of parameters by the algorithm of the *ENVI 5.3* software, which isolates the area affected and underestimated it by considering only the most significant changes.

The supervised classification of images made it possible to categorize the land use and occupation into six classes: trees, ground vegetation, mining tailings, bare soil, water, and urban area. The classifications resulting from the global accuracy and Kappa index were confirmed, showing the excellent performance of the classifier. The classification of images also made it possible to prove and quantify the large devastation caused by the collapse of the dam.

Further studies are needed to quantify the affected area from the dam to the Paraopeba River, considering the total area affected by the disaster.

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Análise espaço-temporal do rompimento da barragem de rejeitos no município de Brumadinho-MG

Resumo

A atividade mineradora consiste em uma das mais importantes atividades econômicas tanto quanto no mundo. As atividades de mineração são reconhecidamente de elevado impacto ambiental. Devido ao tamanho de algumas operações, a quantidade de carga movimentada e os rejeitos gerados, a mineração tem representado riscos para diversas regiões e populações, eventualmente afetadas por acidentes e mecanismos ineficientes de deposição e monitoramento. O Sensoriamento Remoto tem sido cada vez mais utilizado para mapeamento de grandes áreas ou áreas de difícil acesso, por meio dele, é possível obter informações sobre objetos ou fenômenos na superfície da Terra sem que haja contato físico com eles, constituindo-se em uma importante fonte de dados que pode ser utilizada para as mais diversas finalidades. As imagens utilizadas em Sensoriamento Remoto proporcionam uma visão sinóptica e multitemporal de grandes áreas da superfície terrestre, sendo uma alternativa viável em estudos ambientais. O presente trabalho tem como objetivo avaliar a extensão da área afetada pelo rompimento da barragem de rejeitos da companhia Vale na mina do Córrego do Feijão, no município de Brumadinho - MG, ocorrido no dia 25 de janeiro de 2019, que causou um impacto ambiental que será sentido por anos. Para analisar a dimensão do impacto ambiental, foram utilizadas imagens de satélite da constelação Planet com resolução espacial de 3,0 metros. A metodologia utilizada foi baseada no processamento digital de imagens utilizando o *software* PCI *Geomatics* e o *software* ENVI 5.3, com os quais foi possível quantificar a área afetada. Dois diferentes métodos foram utilizados e os valores obtidos foram comparados com os valores divulgados pela Secretaria de Estado de Meio-Ambiente e Desenvolvimento Sustentável de Minas Gerais. Como resultado obteve-se uma área de 2,964096 m^2, desde a barragem até o rio Paraopeba.

Palavras-chave: Sensoriamento Remoto, Impacto Ambiental, Processamento Digital de Imagens.

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