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Analysis of the impact on vegetation caused by abrupt deforestation via orbital sensor in the environmental disaster of Mariana, Brazil

Carlos Antonio da Silva Junior[a,*], Andressa Dias Coutinho[a], José Francisco de Oliveira-Júnior[b], Paulo Eduardo Teodoro[c,*], Mendelson Lima[a], Muhammad Shakir[d], Givanildo de Gois[b], Jerry Adriani Johann[e]

[a] Geotechnology Applied in Agriculture and Forest (GAAF), State University of Mato Grosso (UNEMAT), 78580-000, Alta Floresta, Mato Grosso, Brazil
[b] Institute of Atmospheric Sciences, Federal University of Alagoas (UFAL), 57072-900, Maceió, Alagoas, Brazil
[c] Federal University of Mato Grosso do Sul (UFMS), Chapadão do Sul, Mato Grosso do Sul, Brazil
[d] Institute of Space Technology Islamabad Pakistan, Islamabad, 44000, Pakistan
[e] Western Paraná State University (UNIOESTE), Cascavel, Paraná, Brazil

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ABSTRACT

The failure of the Fundão Dam in Mariana, more precisely in the subdistrict of Bento Rodrigues, state of Minas Gerais (Brazil) on November 5th, 2015, is considered to be "the biggest environmental tragedy in the country's history." About thirty-four million cubic meters of tailings were dumped into the river where, another 16 million continued to reach the Atlantic ocean. This disaster seriously affected the flora, fauna, economic activities and people's lives, including the loss of human lives. Remote sensing allows mapping the variability of terrain properties, such as vegetation, water and geology, both in space and time, offering a synoptic view and useful environmental information in future decision making. In this way, this research aims to analyze the impacts of the failure of the Fundão Dam in the municipality of Mariana-MG on the vegetation cover, by means of remote sensing techniques and analysis of digital processing of orbital optical images. In order to analyze the soil cover, Unmixing Espectral Linear Model (UELM) was used in order to separate soil, shade and vegetation classes. Subsequently, Artificial Neural Network (ANN) classification method was applied, followed by Enhanced Vegetation Index (EVI) and Normalized Difference Vegetation Index (NDVI). The results showed a loss of 13.02% of the vegetation, about 1289 ha, and a reduction of 68.57% of shade (water), approximately 1347 ha. The UELM showed to be effective in the separation of each image-fraction, being an important stage for the success of the classification. The EVI was the index that best described the vegetation deficit in the affected areas spilling the sludge from waste.

1. Introduction

Annually, Brazil is affected by several natural disasters like, severe storms, floods, droughts, landslides and forest fires. However, some of the notable ones are, the fire in Vila Socó in 1984; Césio 137 in Goiânia in 1987; Cataguases dam leakage in 2003; Campos Basin Oil Leakage in 2011; and the Ultracargo fire in Santos in 2015.

The identification of areas affected by disasters is one of the main activities in assessing the damage and the affected population. The time to perform this mapping is a fundamental factor (Gillespie et al., 2007) and assists in the adoption of mitigating measures. Obtaining information on the extent of gravity by conventional means is a challenging task especially under early post disaster time where collapse of communication systems and damage to transport systems are common (Bhatt and Rao, 2014).

Mining activity can be considered one of the most impacting in terms of the affected site (Wang et al., 2017a, 2017b). Already, landmines are one of the most destructive environmental consequences in the world (Berhe, 2007). Mineral exploration if not properly managed can destroy all vegetation, radically alters the landscape, and fully disrupt the ecosystem (Popović et al., 2015). In addition, it can cause important consequences outside its coverage area, especially by the discharge of contaminated waste with sediment, chemicals, radioactive metals or altered acidity (Gardner, 2001; Pontedeiro et al., 2006).

Tailings are fine wastes from the mining industry, produced and loaded by suspensions, due to mixing with water (or solutions containing different chemicals) during mineral processing. Deposits of these residues in ponds, generally confined by artificial dams, can pose

* Corresponding author.
E-mail address: pauloeduardoteodoro@gmail.com (P.E. Teodoro).

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a serious threat, especially when there is inadequate handling and management (Meggyes et al., 2008).

Due to the density of the tailings, the damage caused by leaks or ruptures of dams for the accumulation of these materials is much greater when compared to leakage damages of the same volume of water (Penman, 1998). Such incidents can cause considerable damages to the environment, infrastructure, property, and human lives. Therefore, they are posing a potential challenge for management authorities.

Brazilian history is full of disasters. The Fundão Dam failure on November 5th, 2015 is one of them considering it to be one of the greatest environmental tragedy in the country's history. Approximately thirty-four million m^3 of tailings were released into the downstream river (BRAZIL, 2015).

According to IBAMA (Brazilian Institute for the Environment and Renewable Natural Resources), this disaster has seriously affected flora, fauna, economic activities and people's lives, causing the destruction of 1,469 ha (ha) of land surface, including Permanent Preservation Areas (APP). A number of socio-environmental damages were identified along the stretch. The inhabited areas were isolated, houses were destroyed as a result the population was displaced. Habitats were fragmented, wild and domesticated animals were lost in huge numbers. Fishing was restricted due to the contamination of river water. Most importantly the affected population felt insecure from the point of dam failure to the coast.

One of the ways to evaluate this damage is through remote sensing (RS), which has become a fundamental tool in the mapping and monitoring of changes in soil cover (Sever et al., 2012; Ban et al., 2017; Wang et al., 2017a, 2017b). The images of orbital sensors and aerial photographs allow mapping the variability of terrain properties, such as vegetation, water and geology, both in space and time. It provides a synoptic view and useful environmental information for future decision-making, for a wide range of scales, (Van Westen, 2000).

Ban et al. (2017) used a MODIS (*Moderate Resolution Imaging Spectroradiometer*) sensor image to map flood events along the Pampanga river in the Philippines and Poyang, Dongting lake in China. Li et al. (2015) developed a neural network algorithm based on MODIS data for smoke detection in areas of forest fires. Analyzing the NDVI (*Normalized Difference Vegetation Index*) in a RapidEye time-series, Behling et al. (2014) proposed a methodology for automatic mapping of landslides.

Considering the above, this research had the objective of analyzing the impacts of the rupture of the Fundão Dam in the municipality of Mariana-MG (Brazil) in the vegetation cover, by means of remote sensing techniques and analysis of digital processing of orbital optical images.

2. Material and methods

2.1. Study Area

The Fundão Dam of the company Samarco Mineração S/A is located in the subdistrict of Bento Rodrigues, belonging to the municipality of Mariana, in the central region of the state of Minas Gerais, metallurgical zone, Southeast region of Brazil. The study area covers about 40 km (Fig. 1), from the municipality of Mariana to Pedras, between the meridians 43°11′51.71″W and 43°32′26.50″W, and parallels 20°15′48.81″S and 20°16′58.76″S. Although there is a legally expected area of impacts, we seek to evaluate and analyze the disaster that occurred around the accident, especially with regard to the sub-district and the mud trail in the first kilometers. According to the *Köppen-Geiger* climatic classification, two distinct climatic types are described for the municipality: "Cwa" and "Cwb". The first typology (Cwa) predominates in the lowest elevation sites, comprising a humid climate with hot summer, short dry season and average annual temperature between 19.5 and 21.8 °C. The second typology (Cwb), predominant in the higher elevations, is characterized by mild summer and low annual average temperature (17.4–19.8 °C). December, January and February are the ones that register the highest rainfall regimes, with an annual average rainfall of 1800 mm (Álvares et al., 2013).

The region possesses diversity in vegetation from the terrestrial flora in the area of natural fields in zones of undulated relief to the grasses, cyperaceous and the natural forests area, with trees of medium and high size (Souza, 2004).

2.2. Orbital Remote Sensing

Two orbital scenes of the OLI (*Operational Land Imager*) sensor were used aboard the Landsat-8 satellite, with spatial resolution of 30 m, at path 217 row 74, obtained from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/).

Landsat-8 took forward the Landsat program, where major development has been seen in sensors. The addition of two new bands that responds to aerosols and cirrus clouds, while two in thermal region make it more sophisticated to be used for such applications. In addition to above the finer radiometric resolution and better signal to noise ratio and its free availability compel researchers to use these data (Silva Junior, 2014).

Characterization of the Landsat-8/OLI system/sensor is presented by the moderate spatial resolution (15 m in the Panchromatic and 30 m in the Multispectral bands) of the terrestrial surface in the following spectral regions: spectral band 1 for coastal/aerosol of 0.43 to 0.45 μm; spectral band 2 of blue from 0.45 to 0.51 μm; spectral band 3 of green from 0.53 to 0.59 μm; spectral band 4 of red from 0.64 to 0.67 μm; spectral band 5 of near infrared (NIR) of 0.85 to 0.88 μm; short-wave infrared spectral band 6 (SWIR-1) from 1.57 to 1.65 μm; spectral band 7 of SWIR II from 2.11 to 2.29 μm; and spectral band 9 for cirrus of 1.36 to 1.38 μm (NASA, 2017).

2.3. Digital Image Pre-processing

The original OLI images were submitted to pre-processing. In the preliminary treatment of raw data, the images were radiometrically corrected, geometric distortions were removed and decreased atmospheric effects. By means of the radiometric calibration process in the ENVI 5.1 systems (EXELIS, 2014), all bands of both scenes were transformed from digital numbers (DN) into radiance measurements at the Top of the Atmosphere (TOA). Such a conversion is only possible for scenes that present Metadata files, enabling the process present in Eq. (1).

$$L\lambda = Gain * DN\ do\ pixel + offset \quad (1)$$

where: $L\lambda$: radiance (W. m^{-2}.sr^{-1})DN: digital number$Gain$ and $offset$: factors of image brightness correction, providing improvement in the quality of image contrast.

The second stage of the pre-processing was the atmospheric correction by the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) model, being adopted tropical atmosphere and continental aerosol model. FLAASH operates in the spectral range between 0.4 and 2.5 μm, and the processing is done pixel by pixel. The model starts from the radiance image that arrives at the sensor and allows by obtaining the surface reflectance from the derivation of atmospheric parameters such as albedo, surface altitude, water vapor column, optical depth of aerosols and clouds, besides the surface and atmosphere temperatures (Kruse, 2004).

2.4. Digital Classification

After the treatments performed on the OLI an image, the pixel-to-pixel supervised classification was applied, based on the Unmixing Espectral Linear Model (UELM) (Eq. 2). This algorithm aims to estimate the proportion of the components (endmembers), such as soil, shade and vegetation of each pixel, from the spectral response in the various spectral bands of the OLI, generating the images fraction (Shimabukuro