DOCE RIVER PLUME AFTER THE DAM COLLAPSE: ASSESSMENT BASED ON CBERS-4/MUX SENSOR

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ABSTRACT

The Fundão mine-tailing dam collapse in the Doce River on November 2015 was the most devastating natural hazard in Brazilian history, resulting in a loss of more than US$ 1 billion in property damage and the death of 20 people. In addition, it is estimated that 60 million m³ of toxic mud have reached the Atlantic Ocean after going through more than 600 km downstream. Almost three years after this disaster researchers are still addressing its environmental impacts. In this context, the present study aimed to identify the Doce River plume after the disaster, using Linear Spectral Unmixing Model (LSUM) coupled with images acquired by the CBERS-4 Multispectral Camera (MUX). The results are compared to the natural river plume during previous flood season and to the results obtained with Landsat-8 Operational Land Imager (OLI).

Key words — remote sensing, linear spectral unmixing, seasonality index.

1. INTRODUCTION

Floods are among Earth's most common and destructive natural hazards. However, not all floods are natural events, some of them are caused by human actions. When floods occur, they can cause huge losses to life and property. It typically leaves some economic damage in its way, the severity of which depends on the affected population's resilience and available infrastructure. Usually, poorer countries tend to struggle to recover from the damages caused by a severe flood event [1].

In Brazil, the Doce River watershed encompasses an area of more than 83 thousand km^2, being the second longest river in the Southeast Atlantic Basin [2]. On the 5th of November 2015 the Fundão mine-tailing dam in the Doce River collapsed, resulting in a flood responsible for the death of 20 people and the destruction of the district of Bento Rodrigues in Mariana municipality, Minas Gerais state [3]. Furthermore, it is estimated that within 17 days after the collapse of about 60 million m³ of iron-ore mining residue reached the SW-S Atlantic Ocean [4]. The environmental impacts caused by flood wave for more than 600 km downstream along with the dispersion of its plume in the Atlantic Ocean have categorized this event as the worst environmental disaster in the country's history [3].

Sediment transport to the ocean is a key component in the maintenance of biodiversity and the coastal biogeochemical cycles [5]. However, a high concentration of sediments may negatively impact the environment by means of eutrophication [3]. Temporarily suspended particles, i.e. sediments, are also responsible for the reactivity and exchanges of chemical constituents between the bed sediment and the water column due to resuspension processes, deposition, and generation of particles [6]. Therefore, in addition to the transport of high concentrations of sediments, the collapse of the mine-tailing dam may also result in the reinjection of chemical contaminants for long accumulated in the sediment bed [7]. As a matter of fact, *in situ* studies carried in the Doce River just after the event have found As, Pb, Cd, Cr, Ni, Se, and Mn levels that exceed the legally acceptable values [2]. In addition, high mobilization potentials are also estimated for Ba, Sr, Fe, and Al [2]. Despite the importance of *in situ* studies, there is still a need for a better spatial and temporal representativeness crucial for understanding the rapidly altered interactions between suspended sediment and seawater [5].

Since these hydrodynamic effects quickly change the optical properties of coastal waters, remote sensing techniques can map the spatial and temporal patterns of river plumes [5]. Several remote sensors have been used for monitoring coastal environments. Among them, applications based on Terra and Aqua MODIS, SeaWiFs, Landsat TM, ETM+ and OLI, Sentinel-2 MSI, Sentinel-3 OLCI, Envisat MERIS, NPP and NOAA-20 VIIRS, MSG-3 SEVIRI, CBERS-2B CCD and WFI, HJ-1A CCD, and Resourcesat LISS and AWIFS [3, 4, 7] stand out. When analyzing plume dispersion, no single sensor can fulfill the spatial, temporal, radiometric and spectral requirements for completely understanding the process. Instead, a combination of sensors, with similar spatial, radiometric, and spectral features, but different revisit, is encouraged for following the plume evolution through the ocean [8]. It should be mentioned that among all possible band combinations those based on the visible and near infrared part of the spectrum are commonly used for analyzing turbid coastal waters [3, 4, 5, 8].

Image classification methods have been traditionally used for a vast range of applications in remote sensing [9]. When analyzing sediment though one may be interested not only in the identification of turbid areas but also infer about the sediment concentration. Therefore, the approach by using Linear Spectral Unmixing Model (LSUM) allows the discretization of each pixel component and stands out as a distinct alternative.

The China-Brazil Earth Resources Satellite 4 (CBERS-4) was launched on December 7, 2014, carrying a multispectral camera (MUX), with 20 m spatial resolution, 4 spectral bands, 120 km swath width and a normal revisit time of 26 days. However, its images have been poorly explored so far. In this context, the present study aimed to assess the impacts derived from the Fundão mine-tailing dam collapse on the natural Doce River plume using CBERS-4/MUX images. A set of images was used to build a temporal discretization of the plume dispersion after the event. The results were compared to the natural river plume based on its flood season assessed by seasonality index [11]. To quantitatively characterize the sediment in terms of its optically active components, the LSUM was applied. Then the results derived from CBERS-4/MUX images were compared with Landsat-8/OLI data.

2. MATERIAL AND METHODS

2.1. Study area

The Doce River watershed is located between the states of Minas Gerais (upstream) and Espírito Santo (downstream), encompassing a drainage area of more than 83,000 km² [3]. However, the study area is in the ocean near the mouth of the river (Figure. 1).

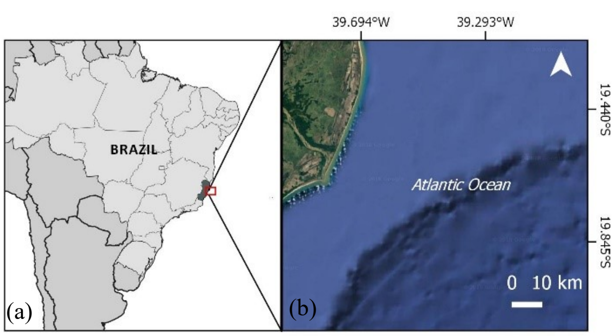

Figure. 1 (a) Doce River mouth in Brazilian coast, Espírito Santo state; (b) Google Earth v7.3.2.5491, December 13, 2015.

According to the climatological normal, total annual precipitation varies from 1000 mm in the coastal regions up to 1600 mm in higher altitudes [12]. Its Köppen climate classes are Aw (tropical wet and dry climate) – with dry winter near the coast and humid subtropical with hot and temperate summer, Cwa and Cwb respectively, for most of its remaining areas [12].

2.2. Hydrological data description

The nonparametric Mann-Kendall test is widely used for detecting linear trends in historical hydrological series. Stationary historical series are those that do not present significant temporal variations by means of trends, shifts and periodicities [13]. This test was applied to the maximum and minimum annual streamflow series for the Doce River, derived from its historical streamflow series. The historical series for the Doce River discharge was provided by the National Water Agency (ANA) and encompasses a period from 1986 to 2015. No data was available after the mine-tailing dam collapse.

Directional statistics, such as the seasonality index are commonly used in hydrology for describing periodic hydrological series [11]. Based on this method, seasonality may be interpreted by its 'Julian Mean Day of Flood' and a measure of the temporal variability of flood occurrences given by the resulting vector $\bar{r}$, where values of $\bar{r}$ can range between 0 and 1. Higher values of $\bar{r}$ suggest that all extreme events occur almost at the same time of the year (i.e. strong unimodal seasonality). $\bar{r}$ values close to 0 represent an even, bi-modal or multi-modal distribution of events [11]. The results of the seasonality index, indicating the flood season guided the image selection to the LSUM approach.

2.2. Linear Spectral Unmixing Model (LSUM)

The surface reflectance of each band was obtained by applying geometric and atmospheric corrections following the recommendations of [14].

The linear spectral unmixing approach assumes that the reflectance of each single pixel is a linear combination of all its constituents [10]. The weight of each constituent is estimated based on the reflectance spectrum of each endmember (i.e. river plume, natural river plume, ocean and cloud). The LSUM may be written as [10]:

$$R_i = \sum_{j=1}^{n} \left(a_{ij} x_{ij}\right) + e_i (1)$$

Where, R_i is the resulting pixel reflectance in band i for a pixel composed by j components (from a total of n components); a_{ij} is the i_n band individual component reflectance, which corresponds to a proportion x_{ij} of the pixel ($0 \leq x_{ij} \leq 1$), and e_i is the error of each spectral band. The condition ($0 \leq x_{ij} \leq 1$) is very computational costing and was neglected in the processing.

CBERS-4/MUX bands 1 to 4 (480, 550, 660 and 830 nm, respectively) were used in the LSUM approach, covering the visible and near infrared spectrum. Landsat-8/OLI correspondent bands 2 to 5 (480, 560, 660 and 860 nm) were used to compare the results of CBERS4/MUX LSUM.

3. RESULTS AND DISCUSSION

3.1. Doce River data

According to the Mann-Kendall stationarity test no significant monotonic trend is observed for the maximum annual streamflow series. On the other hand, a significant decrease in the minimum annual streamflow series was identified, thus characterizing more severe droughts throughout the years. These results corroborate with Rudorff et al. [3], who in an assessment of the Doce River plume turbidity after the event, also observed an increase in severe droughts.

Previous studies have observed that the dam collapse occurred in the context of consecutive years of severe drought. Moreover, Marta-Almeida et al [4] argue that this may have hampered greater sediment transport making subsequent flood events responsible for the flush of large amounts of deposited mud. According to the seasonality index, the 'Mean Day of Flood' is January 8th. Strong unimodal seasonality is observed for the flood ($\acute{r} = 0.90$) season.

3.2. Linear Spectral Unmixing Model (LSUM)

The reflectance spectrum, used as reference for the temporal evaluation of the river plume was derived from the closest CBERS-4/MUX image available after the collapse (December 7, 2015) for the classes: plume from the dam collapse, clouds, and the ocean, and an image on a flood season before the collapse (January 3, 2015) used to define the natural river plume. The procedure was applied on a Landsat-8/OLI image acquired on December 16, 2015, and the natural plume endmember on January 30, 2015, to compare with the CBERS-4/MUX results (Figure2).

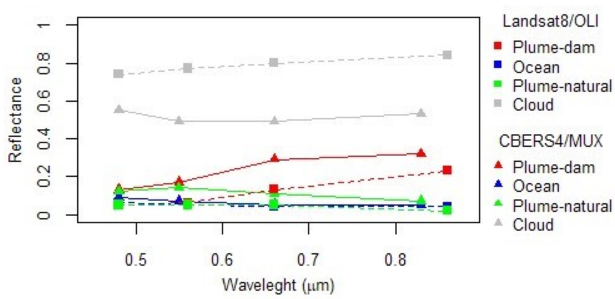

Figure. 2 Reflectance endmembers values derived from CBERS-4/MUX and Landsat-8/OLI imagery used for the LSUM.

In the endmembers spectral response presented in Figure 2 it is possible to notice a clear similarity for both sensors. The responses for the MUX camera though, were, in general, slightly lower than the OLI. Significant differences on surface reflectance are observed between the natural flood season river plume (before the collapse) and the contaminated mud plume (after the collapse) (Figure 2). The growth at the red and infrared parts of the spectrum due to high turbidity levels from the Fundão mine-tailing dam collapse was also observed by Rudorff et al. [3].

In a study using passive tracers and MODIS data, Marta-Almeida et al. [4] concluded that the wind field was the main driver for the dispersion of the Doce River plume into the ocean. The authors showed that predominant southward winds, which are expected for austral spring and summer, are strongly correlated to the southward dispersion of the plume. The results depicted in Figure 3 corroborate with the findings of Marta-Almeida et al. [4].

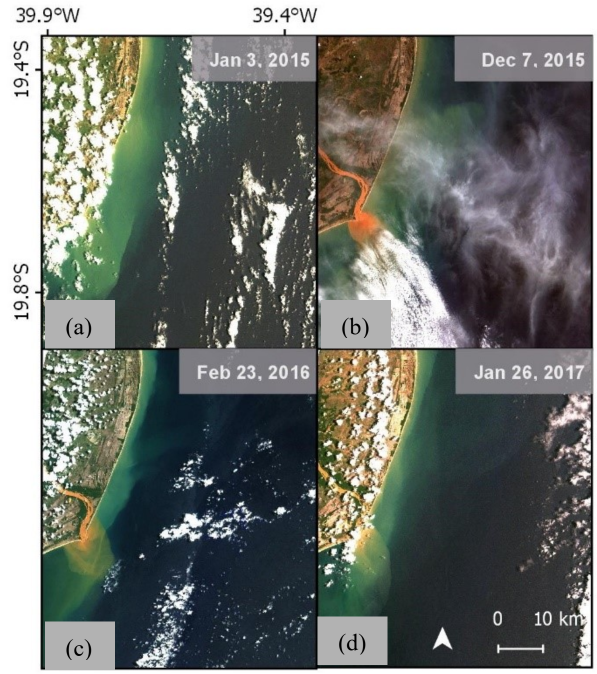

Figure. 3 True color compositions of CBERS-4/MUX, before (a) and after the mine dam collapse (b, c, d).

A clear contrast is observed between the true color RGB composition for the river plume prior to the mine dam collapse (Figure 3a) and just after (Figure 3b) and post-disaster plumes (Figures 3c, 3d). Indications of sediment resuspension, especially during the flood season, may be found for at least two years after the event. Sediment deposition at the Doce River mouth and its later resuspension during flood season may be attributed to the presence of submerged sandbars on its delta [3].

To identify whether the resuspended sediment is a product of the Fundão mine-tailing dam collapse or the natural river plume, the LSUM was performed.

As expected, the image prior to the collapse (Figure 4a) presented a low proportion dam collapse river plume near the river mouth. Followed by a maximum value on the image just after the collapse (Figure 4b), with lower proportions post-disaster (Figure 4c, 4d). The higher levels observed in those images across the ocean may be attributed to its similar reflectance when compared to the natural river plume in the blue and green bands of the MUX imagery (Figure 2).

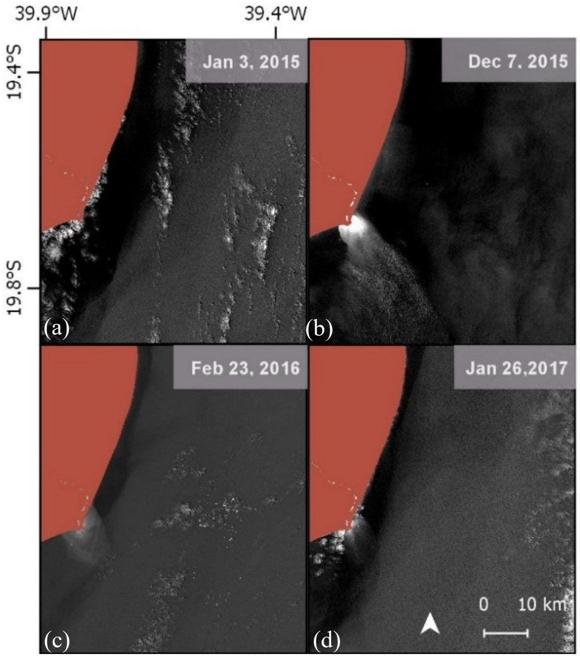

Figure. 4 LSUM results to the fraction of the mud plume before (a) and after the disaster (b, c, d), the gray levels ranging from 96 (black) to 150 (white), land area was masked using brown color.

The mean error involved in the LSUM was ±96 of the absolute value attributed to the pixel (0-255), indicating that endmembers were not completely discretized in the pixel. The mean error obtained in the Landsat-8/OLI was ±90, slightly lower than the obtained for MUX data. These results suggest that the error is mainly derived from the method applied, i.e. number of bands used and pure pixel sampling — difficult to obtain due to the presence of clouds and other atmospheric interferences. Nevertheless, raising the number of bands in the LSUM with the OLI data has not impacted the mean error (±87). Enforcing that the result obtained with MUX is the result expected from the LSUM based on multispectral sensors.

Despite the mentioned errors, clear distinctions between the natural river plume and the dam collapse plume, which are not as clear in the true color composition, are observed in Figure 4. The higher gray levels depicted around the river mouth for the flood seasons of 2016 and 2017 (Figure 4c, 4d), indicate that resuspension is an ongoing process.

4. CONCLUSIONS

LSUM emerges as an important tool for accessing the proportion of specific targets in a given image. According to our results, different seasonal plume patterns are observed for the Doce River plume before and after the disaster. The proposed approach added important information to the analysis since clear distinctions between the natural river plume and disaster derived plume, which may not be identified in the true color composition, are made possible by means of LSUM. Future studies should improve the time discretization by considering other sensors, also investigating the use of the method with hyperspectral sensors. Validation procedures based on *in situ* data are also encouraged.

5. ACKNOLEDGEMENT

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6. REFERENCES

[1] Bankoff, G.; Frerks, G.; Hilhorst, D. "Mapping Vulnerability: Disasters, Development and People". Earthscan, London, 236pp., ISBN 1-85383-964-7. 2003.

[2] Garcia, L.D.; Ribeiro, D.B.; Roque, F.O.; Ochoa-Quintero, J.M.; and Laurance, W.F. "Brazil's worst mining disaster: Corporations must be compelled to pay the actual environmental cost". *Ecological Applications*, v.27, n.1, pp.5-9, 2017.

[3] Rudorff, N.; Rudorff, C.M.; Kampel, M.; and Ortiz, G. "Remote Sensing monitoring of the impact of a major mining wastewater disaster on the turbidity of the Doce River plume off the eastern Brazilian coast", *ISPRS Journal of Photogrammetry and Remote Sensing*, 2018, https://doi.org/10.1016/j.isprsjprs.2018.02.013.

[4] Marta-Almeida, M.; Mendes, R.; Amorim, F.N.; Cirano, M.; and Dias, J.M. "Fundão Dam Collapse: Oceanic Dispersion of River Doce after the greatest Brazilian environmental accident", *Marine Pollution Bulletin*, v.112, n.1-2, pp.359-364, 2016.

[5] Chen, J.; Cui, T.; Qiu, Z.; and Lin, C. "A three-band semi-analytical model for deriving total suspended sediment concentration from HJ-1A/CCD data in turbid coastal waters", *ISPRS Journal of Photogrammetry and Remote Sensing*, v.93, pp.1-13, 2014.

[6] Turner, A.; and Millward, G.R. Suspended Particles: Their Role in Estuarine Biogeochemical Cycles. *Estuarine, Coastal and Shelf Science*, v.55, pp.857-883, 2002.

[7] Mahiques, M.M.; Hanebuth, T.J.J.; Martins, C.C.; Montoya-Montes, I.; Alcántara-Carrió, J.; Figueira, R.C.L.; and Bícego, M.C. "Mud depocentres on the continental shelf: a neglected sink for anthropogenic contaminants from the coastal zone". *Environ Earth Sci*, v.75, n.44, pp.1-12, 2016.

[8] da Silva, A.G.A.; Amaro, V.E.; Stattegger, K.; Schwarzer, K.; Vital, H.; and Heise, B. "Spectral calibration of CBERS 2B multispectral satellite images to assess suspended sediment concentration". *ISPRS Journal of Photogrammetry and Remote Sensing*, v.104, pp.53-62, 2015.

[9] Lu, D.; Weng, Q. "A survey of image classification methods and techniques for improving classification performance", *International Journal of Remote Sensing*, 28(5), 823-870 pp., 2007.

[10] Valerio, A.M.; and Kampel, M. "Uso de Imagens LISS-III para a caracterização espectral da pluma do Rio Paraíba do Sul". *Anais XVI Simpósio Brasileiro de Sensoriamento Remoto*, Foz do Iguaçu-Brasil, 2013.

[11] Chen, L.; Singh, V.P.; Guo, S.; Fang, B.; and Liu, P. "A new method for identification of flood seasons using directional statistics". *Hydrological Sciences Journal*, v.58, n.1, pp.28-40, 2013.

[12] Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; Gonçalves, J.L.M.; Sparovek, G. "Köppen's climate classification map for Brazil". *Meteorologische Zeitschrift*, v. 22, n.6, pp.711-728, 2014.
[13] Wang, Y.; Li, L.; Feng, P.; Hu, R. "A time-dependent index for non-stationary precipitation series". *Water Resources Management*, v. 29, n.15, pp.5631-5674, 2015.
[14] Silva, M.A.O.; Andrade, A.C. "Geração de Imagens de Reflectância de um Ponto de Vista Geométrico". *Revista Brasileira de Geomática*, v.1, n.1, pp.23-30, 2013.