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Orbital imaging of the Furnas reservoir: spatial-temporal variability of the water level and hydrometrics inferences

Imageamento orbital do reservatório de Furnas: variação espaço-temporal do nível da água e inferências hidrométricas

Imágenes orbitales del reservorio de Furnas: variación espacio-temporal de la lámina de agua y inferencias hidrométricas

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Abstract Several variables guide the generation of energy in hydroelectric power plants, two of which are the useful volume and the altimetric quota, and its monitoring is performed mostly by linimetric rulers. The objective of this study is to obtain the spatial-temporal frequency of the water level of the Furnas reservoir, in the period between 1995 and 2019, as well as to adjust regression equations between the parameters water surface area, altimetric height, and useful volume. Thus, images from Landsat 5 and 8 satellites were used to map the water surface and daily data about the altimetric height and the useful volume. The equations between the parameters were adjusted adopting a coefficient of determination bigger than or equal to 0.70 and a 95% confidence interval. The mapping of the spatial-temporal frequency of the water level showed regions of significant oscillation of the water level, near the mouths of the rivers Grande, Verde and Sapucaí, besides the proximities of Campo do Meio and Alfenas. Results show that the statistical adjustment was satisfactory in the estimation of the parameters with R^2 of 0.9805 and 0.9913, for the relations between area versus useful volume and area versus altitude, respectively. The aim of the results is to provide subsidies for actions that guarantee the multiple use of water resources.

Keywords: Hydrology. Remote sensing. Water resources. Multiple uses.

Resumo Diversas variáveis norteiam a geração de energia em usinas hidrelétricas, sendo duas delas o volume útil e a cota altimétrica, sendo seu monitoramento realizado, majoritariamente, por réguas linimétricas. Objetiva-se com este estudo obter a frequência espaço-temporal da lâmina d'água do reservatório de Furnas, no período entre 1995 e 2019, bem como ajustar equações de regressão entre os parâmetros área do espelho d'água, cota altimétrica e volume útil. Para tal, utilizaram-se imagens dos satélites Landsat 5 e 8 no mapeamento do espelho d'água e dados diários de cota altimétrica e volume útil. As equações entre os parâmetros foram ajustadas adotando o coeficiente de determinação maior ou igual a 0,70 e intervalo de confiança de 95%. O mapeamento da frequência espaço-temporal da lâmina d'água apontou regiões de expressiva oscilação do nível da água, próximo às desembocaduras dos rios Grande, Verde e Sapucaí, além das proximidades de Campo do Meio e Alfenas. Resultados demonstram que o ajuste estatístico foi satisfatório na estimativa dos parâmetros com R^2 de 0,9805 e 0,9913, para as relações entre área versus volume útil e área versus cota altimétrica, respectivamente. Almeja-se com os resultados fornecer subsídios às ações que garantam o múltiplo uso dos recursos hídricos.

Palavras-chave: Hidrologia. Sensoriamento remoto. Recursos hídricos. Usos múltiplos.

Resumen: Diversas variables orientan la generación de energía en las centrales hidroeléctricas, siendo dos de ellas, el volumen útil y la cuota altimétrica, y su seguimiento se realiza mayoritariamente mediante reglas linimétricas. El objetivo de este estudio es obtener la frecuencia espacio-temporal de la lámina de agua del embalse de Furnas en el periodo comprendido entre 1995 y 2019, así como ajustar las ecuaciones de regresión entre los parámetros área de espejo de agua, altura altimétrica y volumen útil. Para conseguir esto, se utilizaron imágenes de los satélites Landsat 5 y 8 para cartografiar la superficie del agua y datos diarios sobre la cuota altimétrica y el volumen útil. Las ecuaciones entre los parámetros se ajustaron adoptando un coeficiente de determinación mayor o igual a 0,70 y un intervalo de confianza del 95%. El mapeo de la frecuencia espacio-temporal de la lámina de agua señaló regiones de oscilación expresiva del nivel del agua, cerca de las desembocaduras de los ríos Grande, Verde y Sapucaí, además de las proximidades de Campo do Meio y Alfenas. Los resultados demuestran que el ajuste estadístico fue satisfactorio en la estimación de los parámetros con R^2 de 0,9805 y 0,9913, para las relaciones entre área-volumen útil y área-altitud, respectivamente. El objetivo de los resultados es subvencionar acciones que garanticen el uso múltiple de los recursos hídricos.

Palabras clave: Hidrología. Teledetección. Recursos hídricos. Usos múltiplos.

Introduction

The knowledge on terrestrial dynamics is yet a challenge for the scientific community, because of the characteristics of the phenomena to be monitored, as well as because of the used methods. In this sense, terrestrial observation had expressive increase through the development of spatial programs, with the launching of orbital satellites for non - military ends, especially from the decade of 1970 on.

Among the diverse targets of orbital detection, we highlight the natural bodies of water and/or anthropic, and their monitoring helps in the diagnosis and prognosis of river systems, including the observation of floods and droughts, due to the advance, retreat or recurrence of the water surface, as well as in associations to hydrometric variables, in order to subsidize the elaboration of scientific studies in the most diverse areas of science.

In this regard, the remote sensing ranks as a tool in the help for the monitoring of aquatic areas (BARBOSA *et al.*, 2019), through spectral, radiometric, spatial and temporal characteristics, enhancing the mapping of extensive territorial areas (CRÓSTA, 2002).

Regarding the spectral characteristics of the image sensors, the infrared region is broadly used with the objective of mapping the aquatic areas, because in this area of electromagnetic- spectrum there is higher absorption of radiation (JENSEN, 2009), which causes expressive spectral differentiation between water targets and non-water targets.

However, there is also the use of specific spectral indexes, for the highlighting of aquatic areas, such as the Normalized Difference Water Index (NDWI), elaborated by McFeeters (1996), leaning on green and near infrared bands, as well as the Modified Normalized Difference Water Index (MNDWI), elaborated by Xu (2006), using the green and mid infrared bands.

Then, many authors make use of thresholds for the classification of bodies of water through the analysis of images in the bands of near and mid infrared bands, beyond the aforementioned indexes (CAMPOS *et al.*, 2012; ZHOU *et al.*, 2017; LEONARDO *et al.*, 2021). These classifications can be held in the already consolidated in the desktops environments, through the Geographic Information System (GIS), as well as more recently, through an environment of cloud computing (PEKEL *et al.*, 2016; SOUZA JÚNIOR *et al.*, 2019).

In this last one, we highlight the use of Google Earth Engine (GORELICK *et al.*, 2017), with the work that is developed by the MapBiomas Water Cooperation (https://mapbiomas.org/) and by Joint Research Centre Global Surface Water Mapping (https://global-surface-water.appspot.com/); both make use of the historical series of images by Landsat satellites.

In the regional context from the South of the state of Minas Gerais, the most significant body of water is represented by the reservoir at Furnas Hydroelectric Power Plant (UHE Furnas), which annually registers, according to data from the Brazilian National Water and Sanitation Agency (ANA), through Reservoir Monitoring System (SAR/ANA), relevant vertical oscillations of water levels (ANA, 2022), reflecting in many impacts in the regional economic circuits (LEMOS JÚNIOR, 2010; GODOY, 2017).

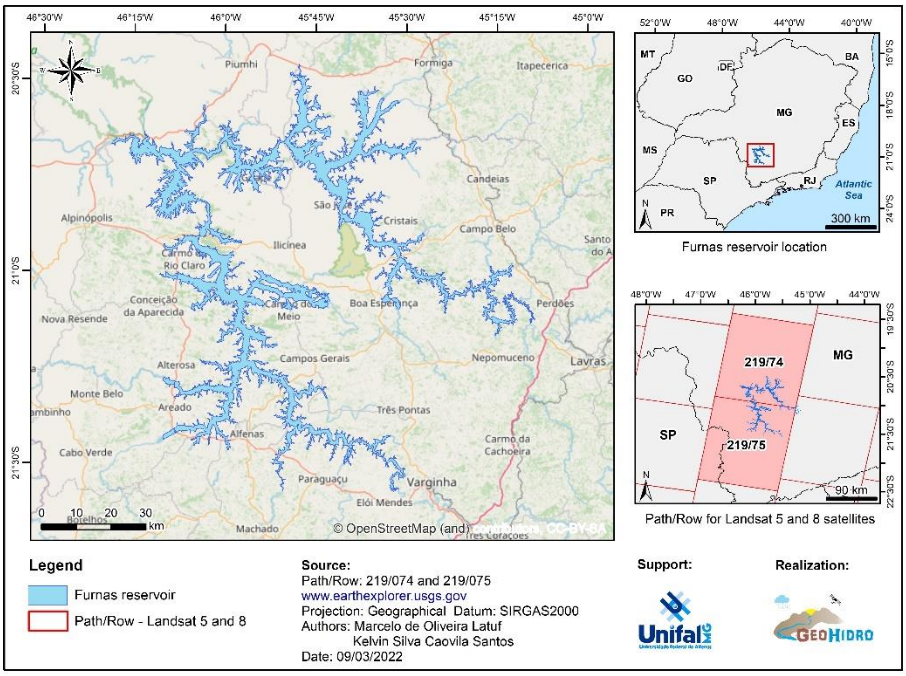
In this context, the present study aims to map the spatial-temporal variation of the water surface at Furnas reservoir, between 1995 and 2019, upon images from catalogues of Landsat 5 and 8 satellites, as well as to adjust regress equations between the parameters of the water surface area, water level and storage capacity, aiming to subsidize planning actions and management of water resources that allow their multiple usages.

Materials And Methods

Location and characterization of the study area

The reservoir of Furnas Power Plant (Figure 1) was planned during the government of the former president Juscelino Kubitschek de Oliveira (1956-1961), attending the increasingly Brazilian energetic demand during that period (BRANDI, 2021). The construction of the dam, which is located between the municipalities of São João Batista do Glória and São José da Barra, in the state of Minas Gerais, started in 1958, with the filling of the artificial lake and the beginning of hydroenergetic generation in 1963 (FURNAS, 2022).

Figure 1 – Furnas reservoir location



As the main affluent water systems in the reservoir, we have Grande, Sapucaí, Verde, Jacaré, Santana and Machado rivers, which form the artificial lake of an area of maximum quota of 1,440km², storing the total of 22.95 billion cubic meters and electrical power of 1,216 megawatts (FURNAS, 2022).

Regarding the annual mean rainfall in the affluent basin to Furnas reservoir, from 1977 to 2006, based in the study from the Geological Survey of Brazil (CPRM, 2011), through the Brazilian Pluviometric Atlas, it was observed the average of 1,528.2mm with standard deviation of 83.5mm.

About the operating band of UHE Furnas (20°40'6.73"S and 46°18'53.81"O), the reservoir has a variation of 18m between operational minimum and maximum, with altimetric quotas that vary between 750m and 768m above sea level, respectively (FURNAS, 2022).

The reservoir is managed by Furnas Power Plants Inc., and it is inserted in the Hydrographic Circumscription in the Surroundings of Furnas Reservoir (IGAM, 2022a), related to the basin of Grande river, and it is placed as a central topic of the actions from the Committee of the Hydrographic Basin in the Surroundings of Furnas Reservoir (CBH Furnas), which had been created by State Decree n. 42,596/2002 (MINAS GERAIS, 2002).

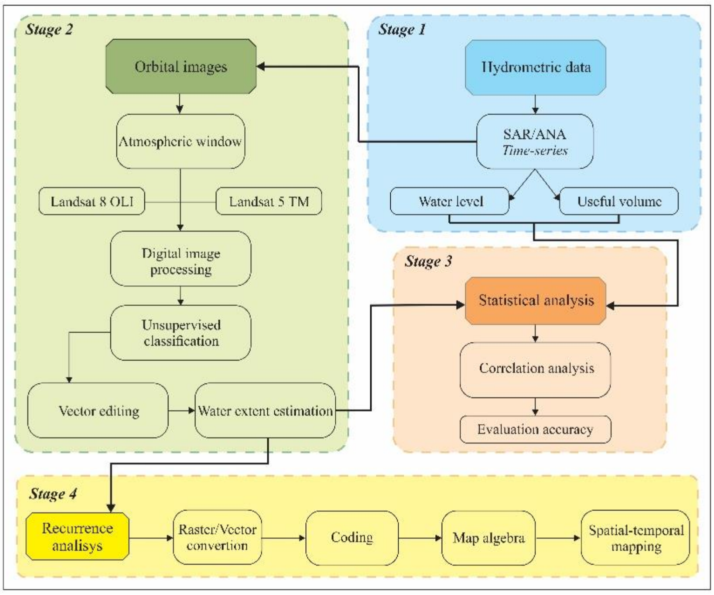
UHE Furnas reservoir directly or indirectly impacts the operational activities of 50 municipalities (IGAM, 2022b), with estimated population, in 2021, of 949,599 inhabitants (IBGE, 2021).

Since its creation, it has become attractive to varied target users, based on the multiple uses of water resources (BRASIL, 1997). However, for decades, there has been conflicts on the use of water resources in the surroundings of the reservoir, as for example the conflicts – and debates – about the oscillations of water levels between the main user (energetic user) and further segments, which are represented, mostly, by the economic chain of tourism (LEMOS JÚNIOR, 2010; GODOY, 2017).

Data acquisition and processing

The methodological proceedings were based on four stages (Figure 2), being the first one characterized by the acquisition of hydrometric data, the second one on the acquisition and processing of orbital data, the third one on the statistical analysis of data and, finally, the fourth and last one which concentrated in the analysis of the recurrence of space-time of Furnas reservoir's water level.

Figure 2 – Survey's methodological flowchart



The acquisition of hydrometric data consisted in the acquisition of daily data of the useful volume (%) and of the altimetric quota (m) of the water level at Furnas, through the access to SAR/ANA, at https://www.ana.gov.br/sar/, where there were acquired , since 1995, the paired data between the two variables.

Regarding stage 2, there were used the orbital images of the satellites Landsat 5 and Landsat 8, Thematic Mapper (TM) and Operational Terra Imager (OLI) sensors, respectively, which were obtained through the site Earth Explorer from the United States Geological Survey (USGS), https://earthexplorer.usgs.gov/. The images were obtained with Level-1 processing (radiometric and geometric corrections), for the path/row 219/074 and 219/075, in the period between 1995 and 2019.

The acquisition of orbital images was guided by the passage of satellites through "atmospheric windows" in the study area, i.e., where there was not detected the presence of clouds or their shadows, on the water surface at Furnas reservoir, because of the characteristics of used sensors.

Digital processing of images consisted on the holding of activities or re-projection and mosaic of near infrared, bands 4 and 5, respectively sensors TM and OLI, with the help of the software Envi 5.0, for each satellite crossing. Soon after, it was decided to reduce the area of resulting image processing, to an involving rectangle which framed UHE Furnas reservoir.

The mapping of UHE Furnas water surface was based in the absorption of the radiant flow through water bodies of near infrared, because Jensen (2009) comments that almost all incident energy in this electromagnetic spectrum band, is absorbed by the water body, resulting in low response of reflectance in this wavelength, which makes these bodies' appearance, expressively contrasting to the emergent surface.

Then, the mapping of the water surface was held through the unsupervised classification method, through the segmentation of images and definition of thresholds through the visual interpretation of the unidimensional histogram of near infrared.

The aforementioned classification procedures were held by the module Feature Extraction, software Envi 5.0 and, soon after its conclusion, the resulting polygons were exported to the shapefile format. Such vector files were used in the vector edition, which aimed the minimization of mistakes in the mapping of the water surface, through screen visual inspection, in the scale of 1:60,000, by using the Editor module of the ArcMap™ 10.6.1, and, in the end, having the quantitative of the area of water surface, in square kilometers.

The evaluation of global accuracy of the mapping, had the insertion of 100 random points through image in infrared band, where they were visually inspected on the screen and labelled in the classes of water or soil. When the classification was finished, the points that had been previously labelled as water, were once again checked for the accounting of assertive points.

Stage 3 refers to statistical analysis between the variables related to water extent (km^2), useful volume (%) and altimetric quota of the water level (m), through the analysis of linear regression, having as adjustment thresholds the value of determination coefficient (R^2) greater than or equal to 0.7 and confidence interval of

95%. The evaluation of accuracy was based on the statistics of the Root Mean Square Error (RMSE), and such procedures were held in a spreadsheet, by using the demonstrative package of plugin XLSTAT©.

Stage 4 was supported in the analysis of spatial-temporal recurrence of the water level of Furnas reservoir and, as basic input for this analysis, there were used the data from stage 2, about the mapped polygons of each crossing of the selected satellites.

The polygons were converted to the matrix format, through the module Polygon to Raster, being further codified with value 1 and, soon after, it was done the sum of all the passages, by using the matrix calculator of ArcMap™ 10.6.1, this way making it possible the elaboration of the mapping of the recurrence of the water level at Furnas reservoir.

Results and Discussion

After the stages and criteria, which had been appointed by the proposed methodological flowchart were fulfilled, there were obtained the monthly and annually recurrences from the orbital imaging of the satellites Landsat 5 and 8 about the water surface at Furnas reservoir.

Because of the prevailing climate – related type in the neighborhood of the reservoir, Humid Subtropical (Cwa), which has remarkable seasonality in the regime of rainfalls along the year (REBOITA, 2015), there were highlighted the months of July, August and September, as the period of higher occurrences of "atmospheric windows", representing 67% of the selected images (Table 1), highlighting the month of August with 15 scenes.

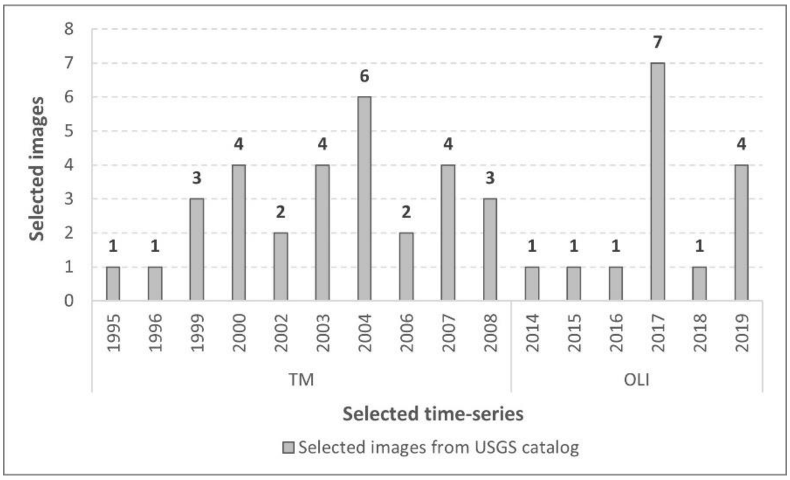
Table 1 – Monthly recurrence of selected images (1995 to 2019)

Month	Images (unit)	Month	Images (unit)
January	0	July	6
February	0	August	15
March	0	September	9
April	3	October	4
May	3	November	1
June	4	December	0

This climate characteristic expressively determined the amount of acquired images, once in the season of rainfalls, between October and March (IGAM, 2013), only 5 images had been selected according to the adopted criteria.

In which regards the annual recurrence of selected images (Figure 3), we highlight the years of 2017 and 2004, with, respectively, 7 and 6 obtained scenes. On the other hand, there were years in which the acquisition of scenes was not possible (n = 9), being 1997, 1998, 2001, 2005 and from 2009 to 2013. This last period without images (5 years) coincided with the end of the operational period of Landsat 5, and the arrangements for the launching of Landsat 8 (EMBRAPA, 2021).

Figure 3 - Annual recurrence of selected images (1995 to 2019)

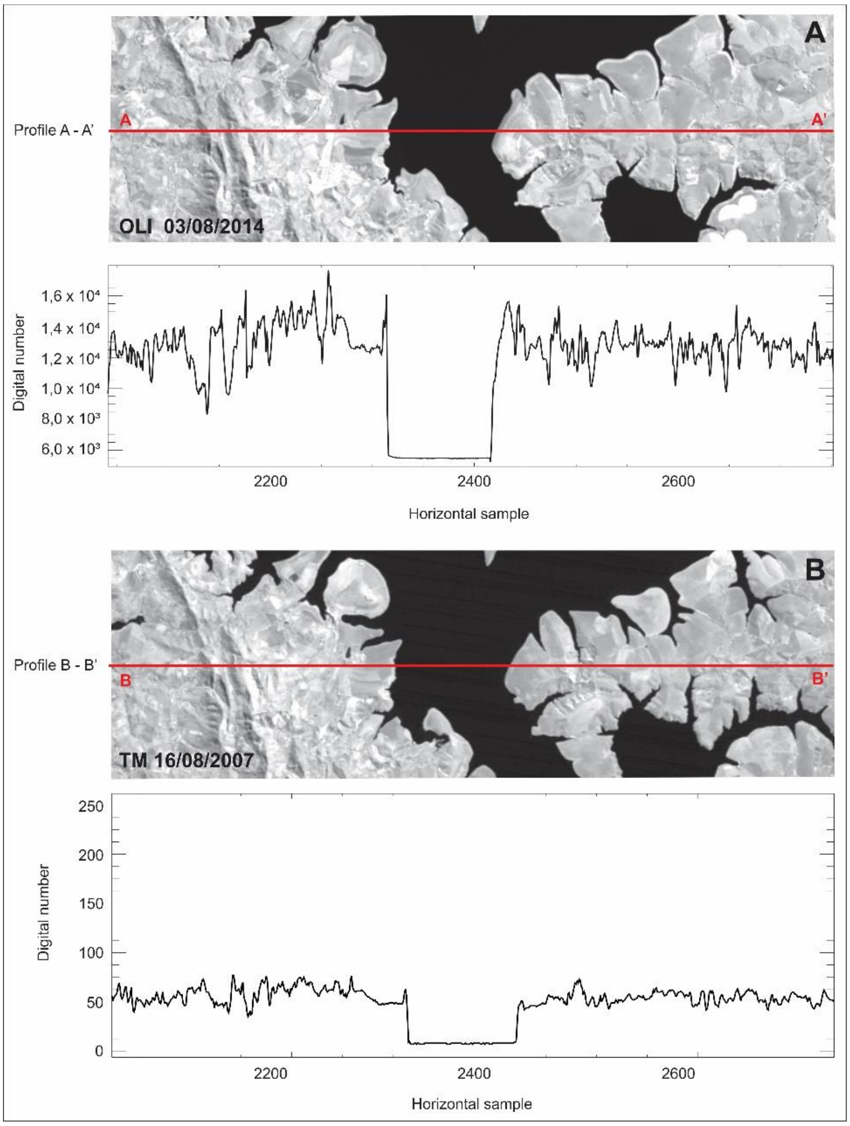


Based on the study time frame (25 years), there is an approximate average of the acquisition of 2 images per year. This unevenness in the distribution of available scenes, with no coverage and shadow of clouds over the reservoir, impacts in the mapping of the water surface, as it has been already mentioned. However, it helps in the detection of areas where there are expressive longitudinal setbacks, which had been caused by the oscillation of the water level in the reservoir.

It is known that optical sensors have limitations in the surface detection, due to the presence of clouds (MONTANHER *et al.*, 2018); nevertheless, there are the sensors with the highest extensions of historical series that are available in catalogues, as for example the Landsat Program (USGS, 2022), which helps in the mapping and spatial -temporal evaluation of the oscillations of many targets, especially Furnas reservoir.

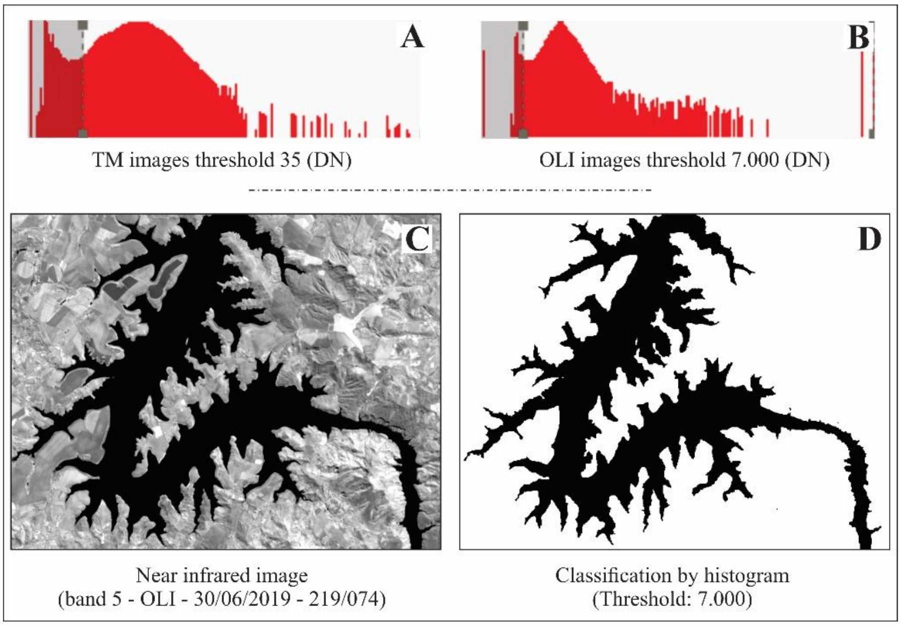
In this context, the mapping of aquatic surfaces was held based on the determination of thresholds for the detection of water. For so, there were evaluated the radiometric responses in different transects that were placed at Furnas reservoir (Figure 4). In Figures 4A and 4B there are highlighted the radiometric profiles in the frameworks of the sensors OLI and TM, respectively, about Furnas reservoir.

Figure 4 – Radiometric profiles of near infrared OLI and TM sensors



It is observed that due to a higher radiometric resolution of sensor OLI, if compared to TM sensor (EMBRAPA, 2021), the differences between the interaction soil and water are more graphically pronounced. Through the interpretation of these transects, there were defined the thresholds for the detection of the aquatic surface for the digital levels of the images of the sensors (Figure 5).

Figure 5 – Thresholds in the detection of Furnas reservoir Furnas (TM and OLI sensors)



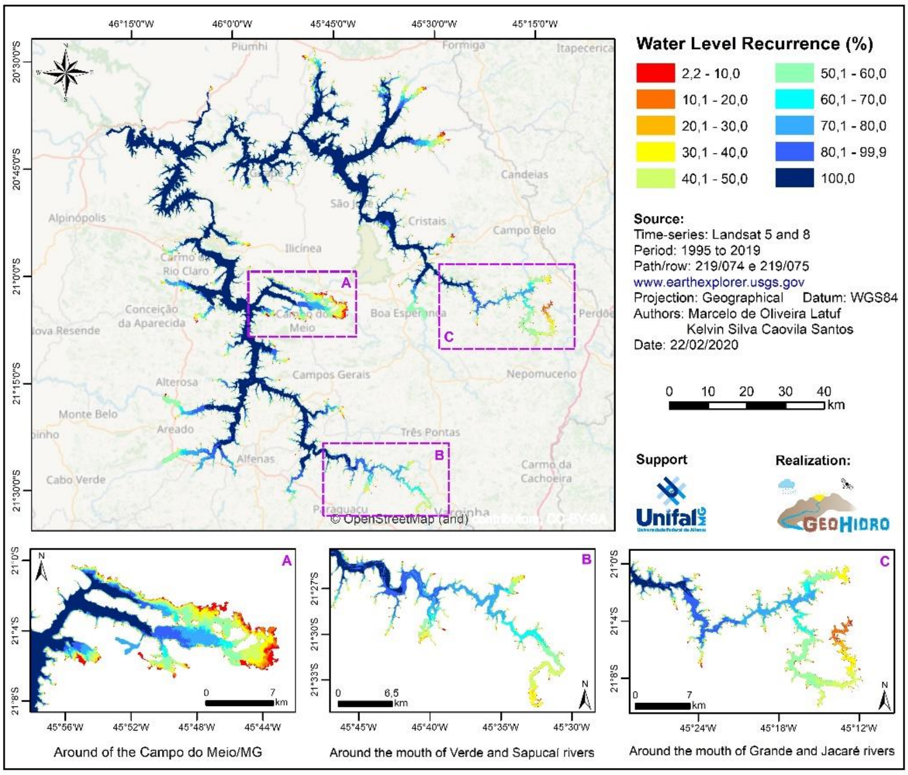
It is observed in Figures 5A and 5B the histograms of frequency of digital levels for two image samples of the sensors TM and OLI, with their thresholds respectively. In Figure 5C, there is a cut of orbit/point 219/074, with crossing date of June 30, 2019, and its classification was viewed in Figure 5D. Through this method, it was evaluated a lower amount of "noises" in the classified image, when compared to the classifications through training samples, which expressively facilitated the stage of vector edition.

About the global accuracy of the mapping of Furnas reservoir between 1995 and 2019, in the end of the classification process, it was obtained the value of 97.3%, which highlights that the procedure reached satisfactory results. However, there were identified some inconsistencies in "small arms" of the reservoir, many of them represented by canyons, when there was a confusion between the differentiation of pixels of water and soil, because of the indentation of these arms and, especially, due to the spatial resolution of the used sensors (30m).

Through the total of selected images (n = 45) between 1995 and 2019, by mapping the water draft in different quotas, it was detected the average area of 1,081.09km², and its variation oscillated between 696.23km² (minimum area, with quote of 754.43m and useful volume of 16.04% on 15/10/2000) and 1,345.73km² (maximum area, with quota of 767.90m and useful volume of 99.18% on 28/04/2008).

Drawing on the database made from the many water surfaces, in the above-mentioned period, it was possible to elaborate the mapping of spatial – temporal recurrence of the water level (Figure 6).

Figure 6 – Water level recurrence at Furnas reservoir (1995 to 2019)



The used color palette to represent the percentual variation of the water level at Furnas reservoir, indicates in local cold colors, where there is higher recurrence of water, between 1995 and 2019, while the hot colors show places where there is reduced permanence of water surface in time.

The analysis of the recurrence of the water level proves that the most affected areas by the longitudinal indentations of the water surface, are located in the surroundings of the municipality of Campo do Meio/MG (Figure 6A), in the area of the mouth of the rivers Verde and Sapucaí (Figure 6B), as well as in the surroundings of the mouths of the rivers Grande and Jacaré (Figure 6C).

Yet, there is highlighted the surroundings of the municipalities of Alfenas/MG, Areado/MG, Alterosa/MG, Boa Esperança/MG, Conceição da Aparecida/MG and Formiga/MG. This latter municipality has declared area of conflict for the use of water resources, since 2019, through the Directive from the Minas Gerais Institute of the Waters Management (IGAM) n. 49 from October 15, 2019 (MINAS GERAIS, 2019).

There are many conflicts because of the use of water resources in the surroundings of Furnas reservoir, and they involve not only the use of superficial waters, but underground ones as well (DEUS, 2021). Yet, according to the study by Deus (2021), the extractions that are directly held at Furnas reservoir, have as a majoritarian destination, the agricultural use through irrigation, with 84% of the bestowals granted by ANA from 2001 to 2020.

On the other hand, the spatial the spatial -temporal evaluation of the recurrence of the water level, pointed out places where there is always water, which does not necessarily meet the demands of the society, as for example the economic circuits of tourism, aquiculture and navigation. In this sense, the presence of water is not enough because, under many circumstances, surface is a determinant variable in the earnings or losses through economic activities.

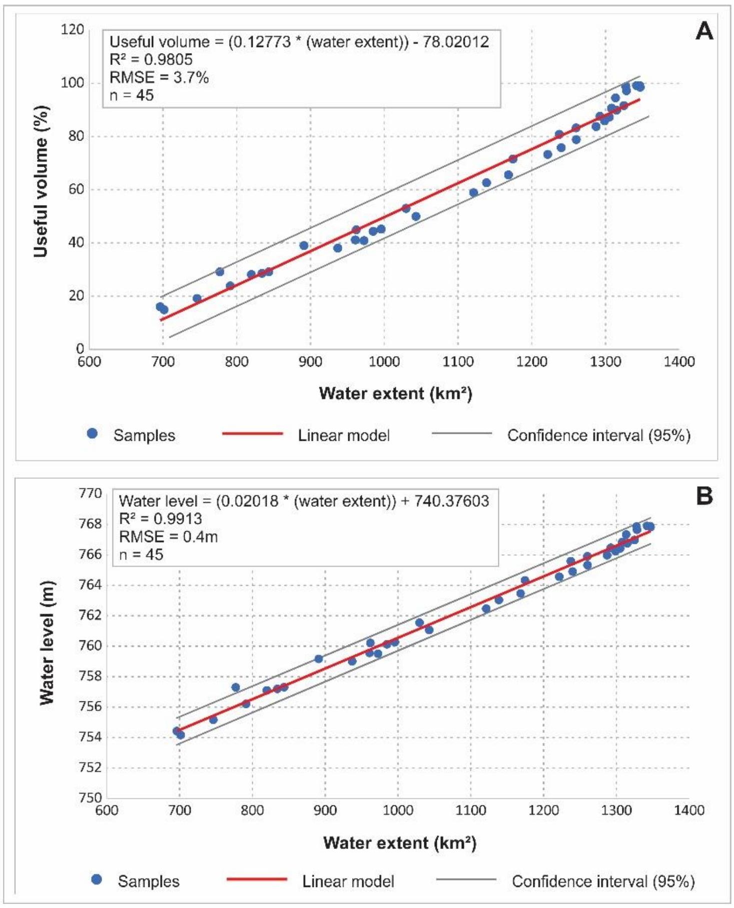
However, it is worth highlighting that the groundskeeping may be associated to the intensity of the longitudinal indentations of the water surface, because in the regions of Capitólio/MG, São João Batista do Glória/MG, São José da Barra/MG, Carmo do Rio Claro/MG and Guapé/MG, for example, there are characteristics of formations of *canyons*, where the vertical oscillation of the water does not cause expressive impacts in the longitudinal indentation.

The mapping of the recurrence of the water level can help the 34 adjacent municipalities to the reservoir (IGAM, 2013) in planning actions and management of the territory, with the purpose of mitigating negative impacts of low temporal occurrence of the water level, in certain regions, as well as to show more appropriate places for activities that demand from the water at Furnas reservoir, as for example, the extraction for human supply and irrigation.

With the mapping of the water surface at Furnas reservoir in different levels, through the images from the satellites Landsat 5 and 8, it was possible to do a statistical evaluation among the hydrometric variables of the water surface (km²), which was obtained through the processing of orbital images with data of water altimetric quota (m) and useful (%), acquired by the system SAR/ANA.

This way, the adjustments between the variables of water extent and useful volume, as well as the area of water extent and water level, were considered satisfactory (Figure 7), based on the coefficients of determination 0.9805 and 0.9913, respectively.

Figure 7 – Statistical adjustments between the hydrometric variables



Through these equations, there were highlighted expressive correlations among the hydrometric variables, which make it possible not only the monitoring of the quota and useful volume through remote sensing, but they especially open perspectives in which refers to the updating of data related to the curve quota -area-volume at Furnas reservoir, according to studies done by Peng *et al.* (2006), Rodrigues, Liebe (2013) and Collischonn and Clarke (2016).

Final Considerations

The results in this study help us to understand the spatial-temporal standards of the reservoir water level at the Furnas Hydroelectric Power Plant from 1995 to 2019, which, in turn, identified more susceptible areas to the indentation of the water surface, and they also subsidize the (re) allocation of economic activities that arise from the multiple use of water resources, aiming the minimization of the caused impacts.

Referring to the estimative of hydrometric variables, useful volume and water level, through orbital images, the gained results are encouraging, based on its spatial-temporal monitoring. Beyond, a new perspective is open for the continuing of researches that involve other variables, as well as the elaboration of models that are associated to the water quality.

About the limitations of the optical sensors that had been used in the monitoring of the reservoir, especially in which refers to the period of rainfalls, the insertion of radar sensing systems, it will enhance the acquisition of images due to their lack of sensitiveness to the coverage of clouds, which will favor the obtaining of images along all the year, independently of the time of the day or weather conditions.

This study aims to contribute to the planning and management of hydric resources in the Hydrographic Constituency in the Surroundings of Furnas Reservoir, providing CBH Furnas, its municipalities and the federal managing body, in the diagnosis of the spatial-temporal variation of the water level, and in the planning of necessary adjustments for the criteria of grants of hydric resources.

It is worth highlighting that the data in this study are available to the society through the Geospatial Data Sharing System (SisGEO), developed by Alvarenga *et al.* (2022), and it can be accessed at https://sisgeo.unifal-mg.edu.br/.

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