Application of spectral indexes in the evaluation of sediment input to the reservoirs of the Itumbiara and Batalha hydroelectric power plants (Brazil)

Aplicación de índices espectrales en la evaluación de la entrada de sedimentos a los embalses de las centrales hidroeléctricas Itumbiara y Batalha (Brasil)

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ABSTRACT

In this work, two spectral indexes were implemented using Landsat images, the Normalized Difference Water Index (NDWI) for the delimitation of the water mirror and the Normalized Difference Turbidity Index (NDTI) to evaluate the sediment contribution to the reservoirs of the hydroelectric power plants Itumbiara and Batalha, located on the borders of the states of Goiás and Minas Gerais. The acquisition and processing were carried out in the Google Earth Engine platform and the post-processing in the QGIS software. The NDTI was applied to the reservoirs considering the variation in water level between the dry and rainy seasons in 2020. The highest concentration of turbidity in the Itumbiara reservoir occurred in September, and the lowest in June. August was the month with the highest turbidity concentration and July the lowest in the Batalha reservoir.

KEYWORDS: Sediment, Hydroelectric Power Plant, Remote Sensing, Turbidity.

RESUMEN

En este trabajo se implementaron dos índices espectrales utilizando imágenes Landsat, el Índice de Diferencia de Agua Normalizada (NDWI) para la delimitación del espejo de agua y el Índice de Turbidez de Diferencia Normalizada (NDTI) para evaluar el aporte de sedimentos a los embalses de las centrales hidroeléctricas Itumbiara y Batalha, ubicadas en los límites de los estados de Goiás y Minas Gerais. El NDTI se aplicó en los embalses considerando la variación del nivel del agua entre las épocas seca y lluviosa de 2020. La mayor concentración de turbiedad en el embalse de Itumbiara se presentó en septiembre y la menor en junio, siendo agosto el mes con mayor concentración de turbidez y julio con la menor en el embalse de Batalha.

PALABRAS CLAVE: Sedimento, Central Hidroeléctrica, Teledetección, Turbidez.

Aplicação de índices espectrais na avaliação do aporte de sedimento aos reservatórios das Usinas Hidrelétricas Itumbiara e Batalha (Brasil)

RESUMO

Neste trabalho foram implementados dois índices espectrais utilizando imagens Landsat, o Índice da Diferença Normalizada de Água (NDWI) para delimitação do espelho d'água e o Índice de Turbidez por Diferença Normalizada (NDTI) para avaliação do aporte de sedimentos aos reservatórios das Usinas Hidrelétricas Itumbiara e Batalha, localizadas nas divisas dos estados de Goiás e Minas Gerais. A aquisição e o processamento foram realizados na plataforma *Google Earth Engine* e o pós-processamento no software QGIS. O NDTI foi aplicado nos reservatórios considerando a variação do nível de água entre as estações seca e chuvosa de 2020. A maior concentração de turbidez no reservatório de Itumbiara se deu em setembro, e a menor em junho. Já no reservatório de Batalha, sendo agosto o mês com maior concentração de turbidez, e a menor em julho.

PALAVRAS-CHAVE: Sedimento, Usina Hidrelétrica, Sensoriamento Remoto, Turbidez.

Application des indices spectraux dans l'évaluation de l'apport de sédiments dans les réservoirs des Centrales Hydroélectriques d'Itumbiara et de Batalha (Brésil)

RÉSUMÉ

Dans ce travail, deux indices spectraux ont été implémentés à l'aide d'images Landsat, le Normalized Difference Water Index (NDWI) pour la délimitation du miroir d'eau et le Normalized Difference Turbidity Index (NDTI) pour évaluer la contribution des sédiments aux réservoirs des centrales hydroélectriques. Itumbiara et Batalha, situées aux confins des états de Goiás et Minas Gerais. Le NDTI a été appliqué dans les réservoirs en tenant compte de la variation du niveau d'eau entre les saisons sèche et pluvieuse de 2020. La plus forte concentration de turbidité dans le réservoir d'Itumbiara s'est produite en septembre et la plus faible en juin. Dans le réservoir de Batalha, août étant le mois avec la plus forte concentration de turbidité et la plus faible en juillet.

MOTS-CLÉ: Sédiment, Centrale Hydroélectrique, Télédétection, Turbidity.

Applicazione degli indici spettrali nella valutazione dell'immissione di sedimenti nei riservi degli Impianti Idroelettrici di Itumbiara e Batalha (Brasile)

RIASUNTO

In questo lavoro sono stati implementati due indici spettrali utilizzando immagini Landsat, il Normalized Difference Water Index (NDWI) per la delimitazione dello specchio d'acqua e il Normalized Difference Turbidity Index (NDTI) per valutare il contributo dei sedimenti ai serbatoi delle Centrali Idroelettriche Itumbiara e Batalha, situate ai confini degli stati di Goiás e Minas Gerais. L'acquisizione e l'elaborazione sono state effettuate nella piattaforma Google Earth Engine e la post-elaborazione nel QGIS. L'NDTI è stato applicato nei bacini considerando la variazione del livello dell'acqua tra la stagione secca e quella piovosa del 2020. La più alta concentrazione di torbidità nel bacino di Itumbiara si è verificata a settembre, e la più bassa a giugno. Nel bacino di Batalha, agosto è il mese con la più alta concentrazione di torbidità e il più basso a luglio.

PAROLE CHIAVE: Sedimenti, Centrale Idroelettrica, Telerilevamento, Turbidity.

Introduction

In recent years, the use of remote sensing techniques and products in hydrological research has become commonplace. Based on water reflectance, satellite images are used for analysis of water quality, sediment concentration, and aquatic flora[1].

The color of water is directly related to its optical properties of absorption and scattering, which vary according to the concentration, nature and type of dissolved and suspended matter in the water[2]. These materials, known as optically active components (OACs), affect the optical properties of water bodies, i.e., the interaction between solar radiation and water[3].

Orbital sensors are capable of registering the effects of the interaction of solar radiation with the components present in water, such as chlorophyll, organic matter, suspended sediments, among others. Based on this knowledge, it is possible to make inferences about the composition and quality of water bodies from remote sensing.

Among the indexes found in the literature, the following are usually employed for various purposes and applications: the Normalized Difference Turbidity Index (NDTI), the Automatic Water Extraction Index (AWEI), the Water Ratio Index (WRI), the Normalized Difference Water Index (NDWI) and its modified version, the Modified Normalized Difference Water Index (MNDWI), among others. Of these, attention is drawn to the NDWI and NDTI.

The Normalized Difference Water Index (NDWI) was developed to highlight the features in water from the digital processing of satellite images, with reference to the presence of optically active components, and is based on the Normalized Difference Vegetation Index (NDVI), established in the literature for detection, characterization and monitoring of vegetation[4]. Positive NDWI values correspond to aquatic environments with higher water purity, while negative or near-zero values represent impurity.

As an example, we cite the application of NDWI to identify suspended sediment fluxes during 2013 and 2014 in the Araguaia River, located on the border of the states of Goiás and Mato Grosso[5]; to evaluate the dynamics of suspended sediment concentration in the Patos Lagoon, Rio Grande do Sul[6]; and delimitation of suspended sediment flux at the Sinop-MT hydroelectric power plant[7]. Overall, the turbidity data obtained by spectral indexes showed good correlation with field data.

Subsequently, the Normalized Difference Turbidity Index (NDTI) was developed specifically for estimating water turbidity, using reflectance bands in the red and green bands of the visible radiation spectrum[8], sensitive to turbidity.

The NDTI has been used frequently to analyze the turbidity variation in water sources and reservoirs, and it has been shown that the turbidity values and those estimated by the index have a positive correlation greater than that verified from other spectral indices[9/10]. In the case of this index, positive values indicate higher sediment concentration, while negative values or values close to zero portray lower turbidity[11].

Thus, in order to contribute to the modeling of sediment contribution in hydroelectric power plants, spectral indexes were used to delimit the water mirror and to qualitatively evaluate the sediment contribution to the reservoirs of Itumbiara and Batalha hydroelectric power plants, located on the borders of the states of Goiás and Minas Gerais, in Brazil.

Methodology

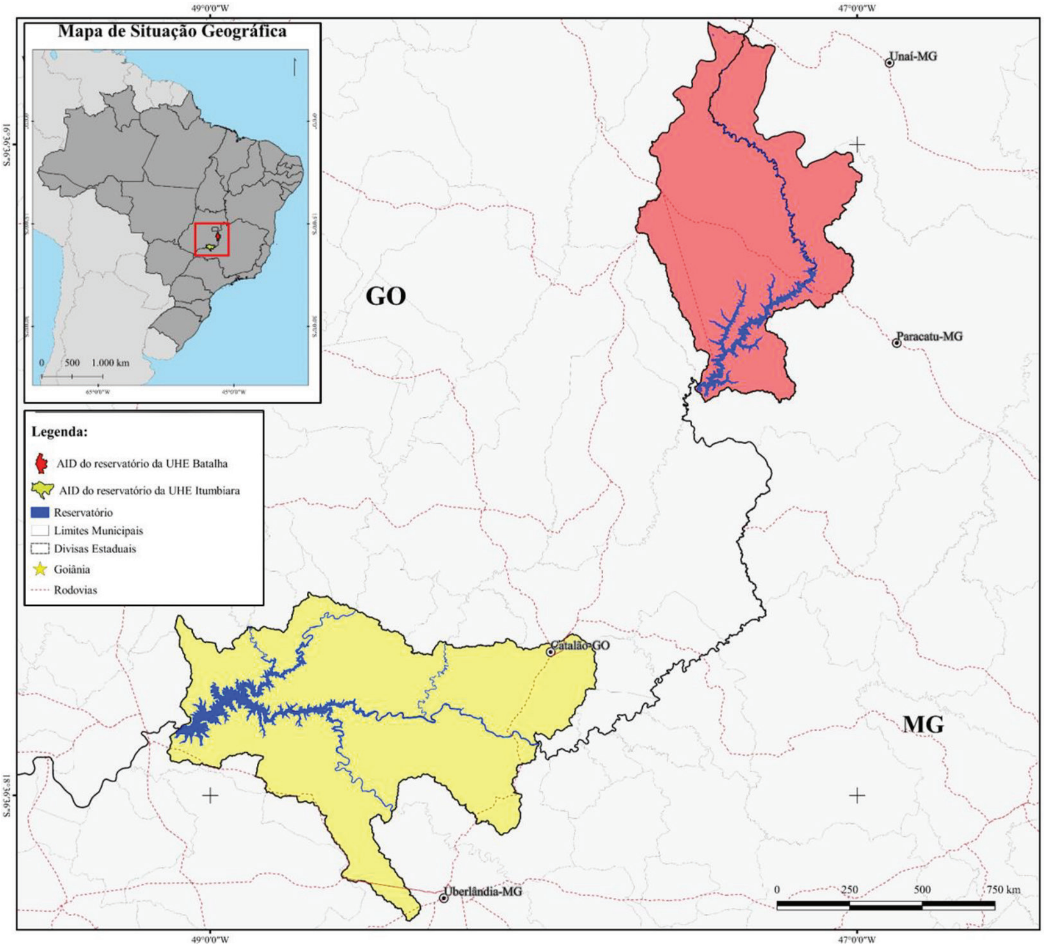
Location and brief characterization of the study areas

The area under study is represented by the Itumbiara and Batalha HPP, located respectively on the border of the state of Goiás (GO) with Minas Gerais (MG), in Brazil (Figure 1). UHE Batalha has an Area of Direct Influence (AID) of 5,156 km², including three municipalities, while UHE Itumbiara has an AID of 7,296 km², including 18 municipalities.

It is important to emphasize that the aforementioned Areas of Direct Influence (ADIs) depict only the contribution basins that flow directly into each reservoir, "disregarding the parts of these basins that were upstream from other reservoirs, since these are capable of retaining most of the fine sediments and of containing a large part of the surface flow of rainwater”[12].

1 Kampel and Novo, 2005.
2 Molleri, Novo and Kampel, 2008, 331-349.
3 Barbosa, Novo and Martins, 2019, 1.
4 McFeeters, 1996, 1425-1432.
5 Borges *et al.*, 2015.
6 Ramos *et al.*, 2019.
7 Simões, 2020.
8 Lacaux *et al.*, 2007, 66–74.
9 Garg *et al.*, 2020.
10 Latuf and Amaral, 2016.
11 Gregório and Ferreira, 2018, 74.
12 Silva, 2022.

Figure 1. Map showing the location of UHEs Batalha and Itumbiara



Source: authors.

UHE Itumbiara started its construction in 1974 and started operating in April 1980. It is a relatively old plant and of considerable relevance in the FURNAS system, with an installed capacity of 2,082 MW and 6 operating units[13]. The Itumbiara HPP reservoir was formed by damming the Paranaíba River, in the hydrographic basin of the Paraná River, and is located between the municipalities of Itumbiara (GO) and Araporã (MG).

UHE Batalha is more recent, its construction began in mid-2008 and operations started in 2014, with an installed capacity of 52.5 MW[14]. The dam is located on the São Marcos River.

From a geomorphological point of view, these areas are located on plateaus, formed by the orogenic belt of the Brasília Belt, which is composed of undulating terrains, including Cambissolos, Latossolos, and Argissolos. Land use in these regions is marked mainly by pasture and agriculture[15], while the climate is predominantly tropical, being hot and semi-humid, with 4 to 5 months of drought. Precipitation is an important climatological variable in these regions, which present a large difference between the dry and rainy seasons.

The annual rainfall in Catalão (Figure 2), whose station is located between the two reservoirs, can be used to explain the seasonality of rainfall in the reservoirs, as it directly reflects the climatic conditions of the region. The total annual precipitation is 1,408 mm, with monthly precipitation values ranging from 4 mm in July to 272 mm in January. The rainiest months are from October to April, with a total of 1,319 mm of rain. The dry season starts in May and lasts until September with a total rainfall of 88.9 mm, with the driest months being in the June-August quarter.

[13] Furnas, 2022b.
[14] Furnas, 2022a.
[15] Silva, 2022.

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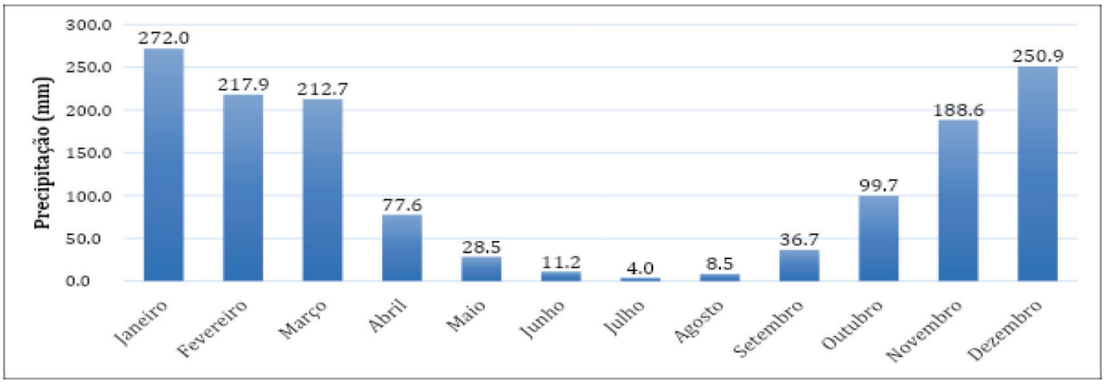
Figure 2. Graph with the monthly precipitation averages in Catalão - GO (1991 to 2020)



Source: Climate Normals from the National Institute of Meteorology.

Methodological proceedings

To meet the proposed objective, the methodological approach consisted initially of a literature review, in order to identify the physical principles, the spectral indexes and the main images used in the analysis of suspended sediments in hydric bodies. To this end, searches were performed in databases such as the Capes Periodical Portal, the Scientific Electronic Library Online (SciELO) and Google Scholar for papers that addressed the themes "spectral indexes" and "suspended sediments", with these expressions serving as keywords.

The next step consisted in the acquisition and processing of images from the Landsat 8 satellite (OLI Sensor) referring to the year 2020, in the Google Earth Engine (GEE) platform. It is noteworthy that the Landsat 8 images comprise pre-computed data, orthorectified and corrected for the interaction of the atmosphere, the latter of utmost importance, since, in the applications of orbital data in the analysis of water composition the premise of atmospheric correction is of fundamental importance[16].

In the satellite data acquisition stage, a filter was applied to return only images with cloud cover less than 20%, causing a significant reduction in the quantity of images, especially in the rainy period (October to March). Thus, images that could portray the dry and rainy periods in the region were selected. Thus, for UHE Batalha images from May, June, July, August and September 2020 were collected and processed, while for UHE Itumbiara the months were April, June, July, September and November of the same year. Therefore, it is not possible to standardize the months for the two areas under study, given the availability of images.

[16] Dash *et al.*, 2012.

Next, the spectral indexes were applied. The Normalized Difference Water Index (NDWI) was used to delimit the water mirror of each of the months (used as a spatial mask), and the Normalized Difference Turbidity Index (NDTI) was used to indicate the monthly variation and the places with higher proportion of suspended sediments. The indexes were calculated according to the following equations:

$$NDWI = (G - NIR) / (G + NIR)$$

Where: G = green (band 3) e NIR = near infrared (band 5)

$$NDTI = R - G / R + G$$

Where: R = red (band 3) e G = green (band 2)

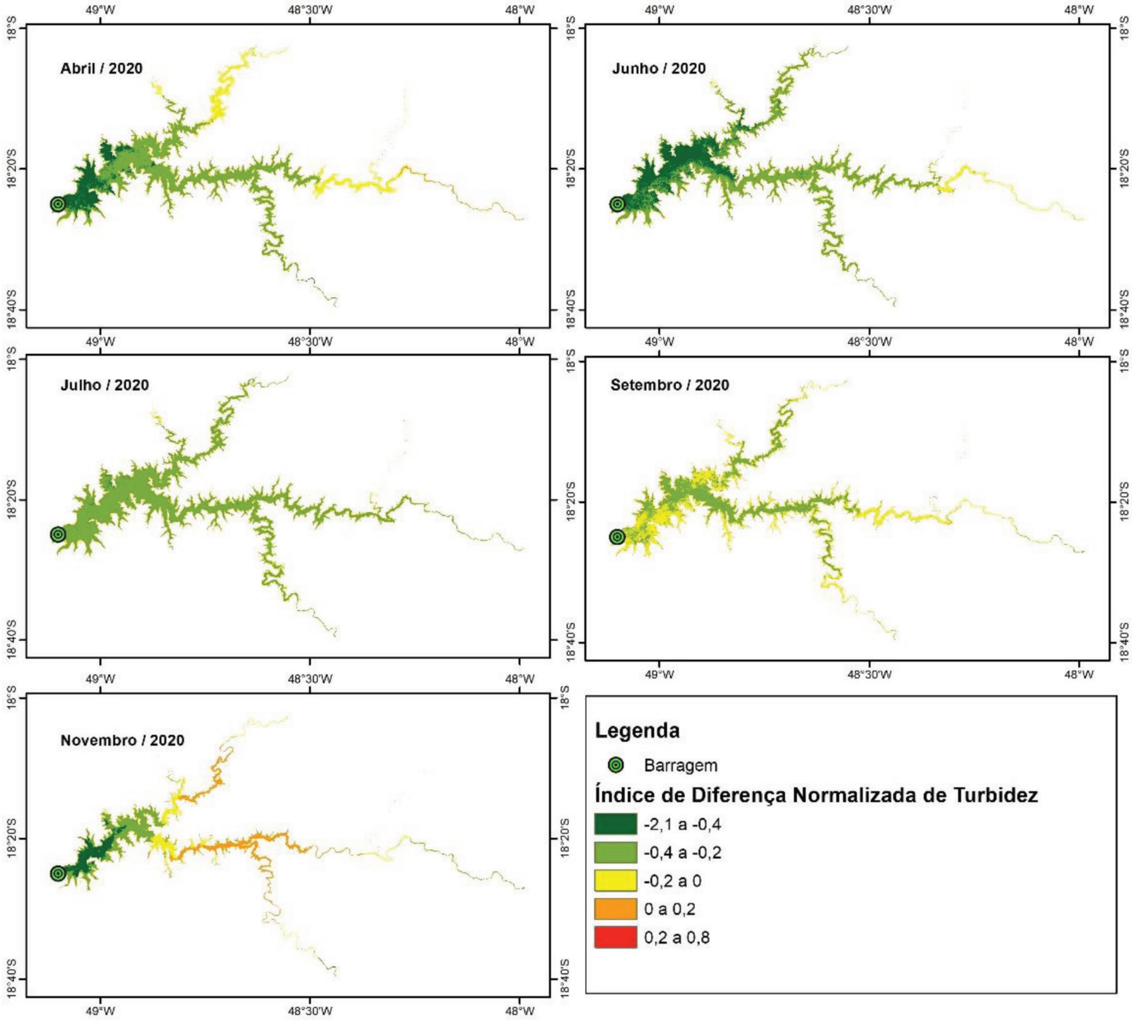
After processing the satellite images for the spectral indexes, they were exported and passed through post-processing in QGIS software version 3.16 (Hannover), for the elaboration of the graphic and cartographic representations and consequent data analysis.

Results and discussions

As previously discussed, the NDWI was applied to the Batalha and Itumbiara HPP reservoirs in each of the images for delimiting the water mirror, considering the variation in water level between the rainy and dry periods in the region.

For UHE Itumbiara, the water mirrors referring to the months of April, June, July, September and November were delimited and then the NDTI was implemented to evaluate the spatial and temporal variation of water turbidity. From Figure 3, it is possible to observe that, in general, the turbidity is lower in the dry season (April, June and July) and increases during the rainy season (September and November).

Figure 3. Water mirror and turbidity variations in the Itumbiara HPP reservoir - 2020



Source: authors.

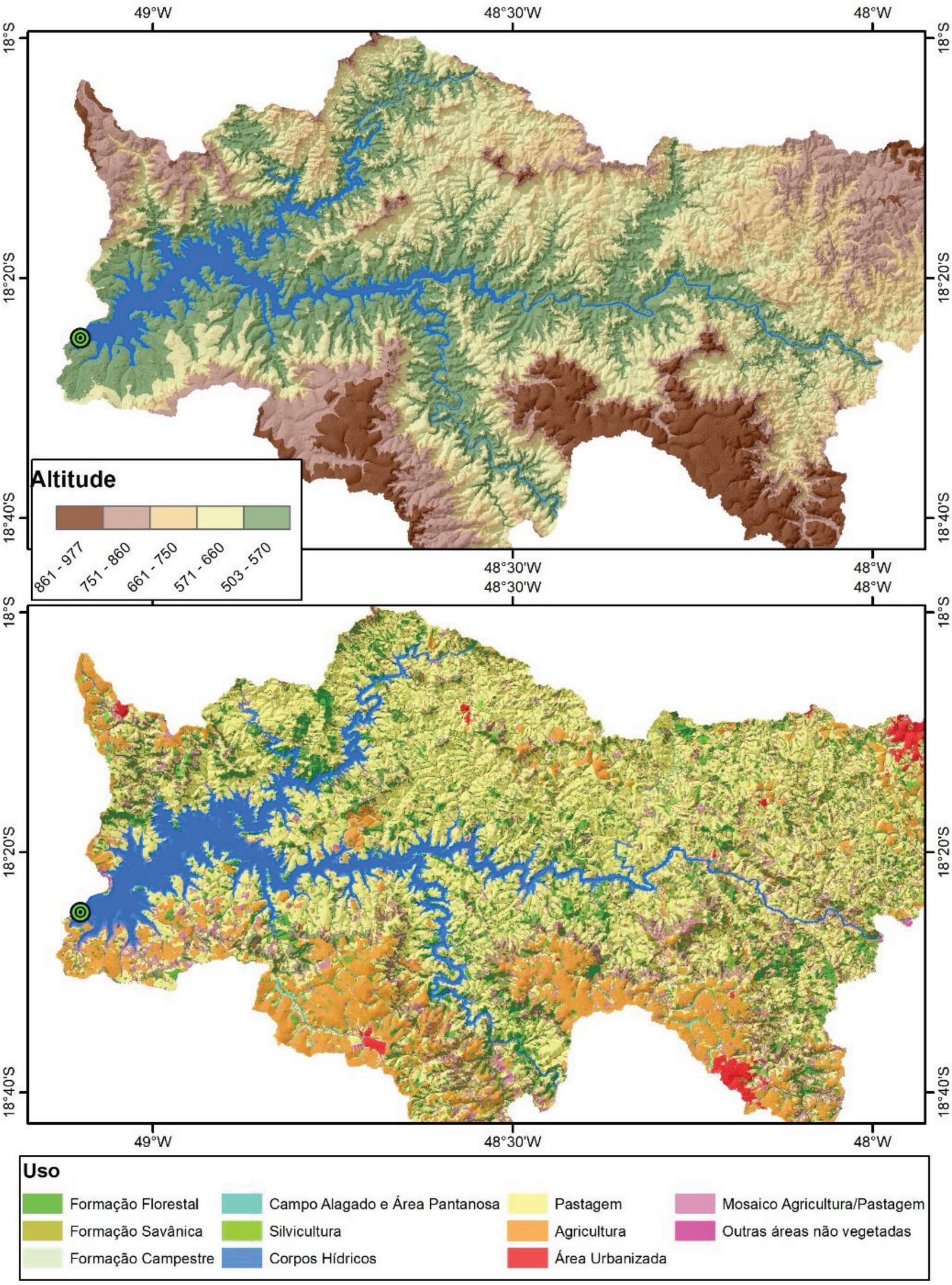
The marked seasonality of rainfall in the study areas, with a large concentration between October and March and a dry period from April to September, as shown in Figure 2, directly influences the temporal variation of suspended sediments, as also indicated by other authors for the Itumbiara reservoir[17, 18], for other hydroelectric power plant reservoirs in Brazil[19, 20] or generally for the watershed context[21]. Another relevant aspect is how the great intra-annual rainfall variability can promote changes in the sediment contribution and, therefore, in the turbidity of reservoirs and water sources, as a reflection of the dynamics of rainfall erosion, which tends to be greater according to the volume and intensity of precipitation[22, 23].

When we observe the spatial variation, i.e., the spatial variation of turbidity in the reservoir, we notice that near the dam the turbidity is lower in all months, while upstream, especially in the east and northeast channels that flow into the reservoir, there is higher turbidity. This spatial variation can be explained by two possible factors, due to the greater depth of the reservoir near the dam and due to the elevation gradient near these channels (~360m) - Figure 4.

Likewise, the land use map shows a predominance of pastures and agricultural activities in these locations, which tend to present exposed soil with high susceptibility to disaggregation and transport, by erosion, of pluvial and fluvial origin (on the edges of drainage channels)[24, 25, 26]. These two aspects, proximity to the dam and exposed soil unprotected by

[17] Cesar, 2011.
[18] Nascimento *et al.*, 2011
[19] Santos and Cunha, 2015.
[20] Dias *et al.*, 2018.
[21] Montebeller, 2009.
[22] Nascimento, 2016.
[23] Costa, Nascimento and Luz, 2022.
[24] Guerra, 1999.
[25] Nascimento *et al.*, 2016.
[26] Nascimento, Romão and Sales, 2020.

Figure 4. Altimetry (in meters) and land use (2020) around the Itumbiara HPP reservoir



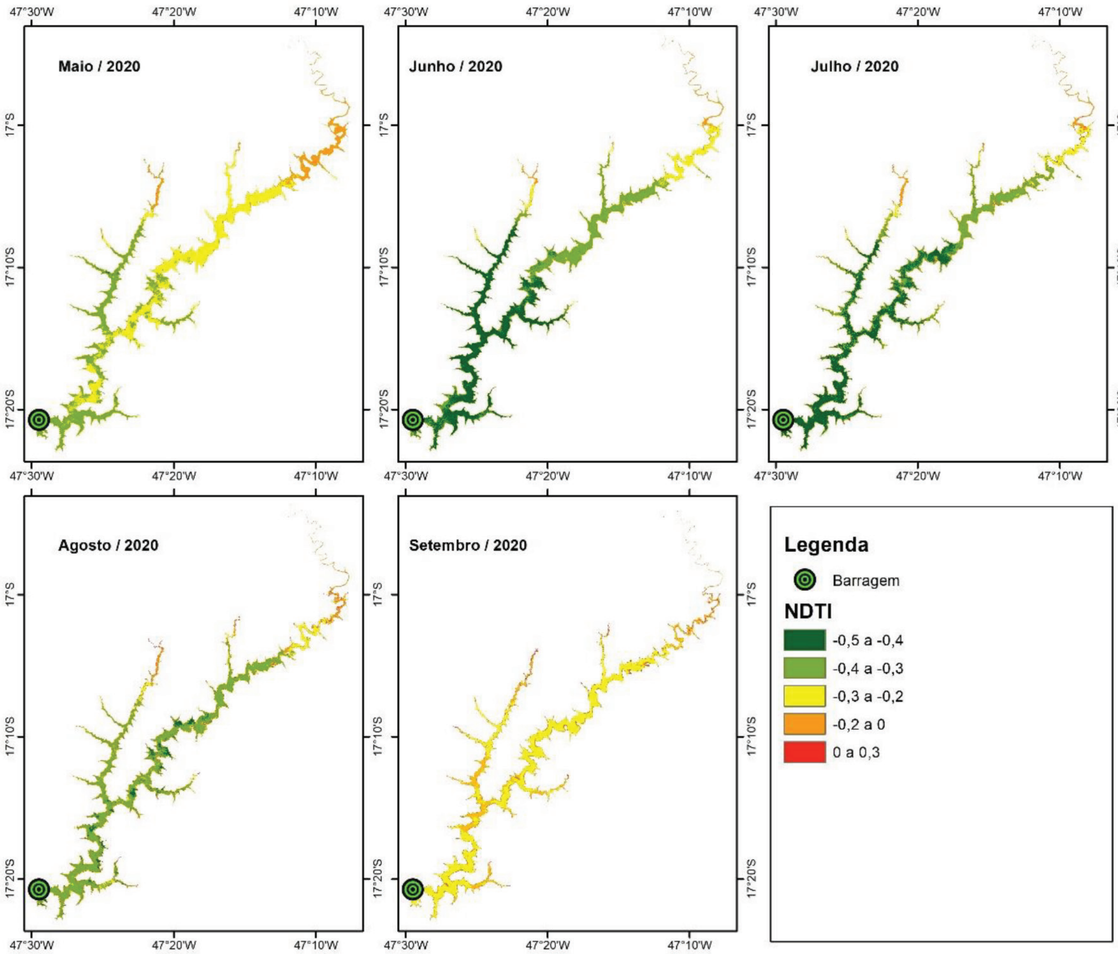
Source: SRTM and Mapbiomas (2021), org. authors.

vegetation, are also pointed out by other authors as being associated with higher turbidity in hydroelectric reservoirs[27, 28, 29].

For the UHE Batalha reservoir, the water mirrors were delimited and the spatial-temporal variation of turbidity was evaluated throughout the months of May, June, July, August and September 2020 (Figure 5). The months characteristic of the dry season (June to August) showed a lower proportion of suspended sediment, while May and September, which mark, respectively, the end and beginning of the rainy season, showed higher turbidity.

[27] Cabral *et al*., 2009
[28] Facco *et al*., 2021
[29] Nascimento *et al*., 2011

Figure 5. Water mirror and turbidity variations in the UHE Batalha reservoir - 2020



Source: authors.

Similarly to the case of UHE Itumbiara, for UHE Batalha it is also possible to see that the portion closest to the dam, with greater depth of the reservoir, presents less turbidity, while upstream of the reservoir there is a greater proportion of suspended sediments. However, the condition of the topography (altimetric gradient) and the use of the soil (predominance of agriculture and cattle-raising), demonstrated by the maps of Figure 6, did not make it possible to observe the causes of the spatial variation of turbidity in UHE Batalha. In this case, it is quite possible that the reservoir depth is the main conditioning factor for the spatial variation of turbidity.

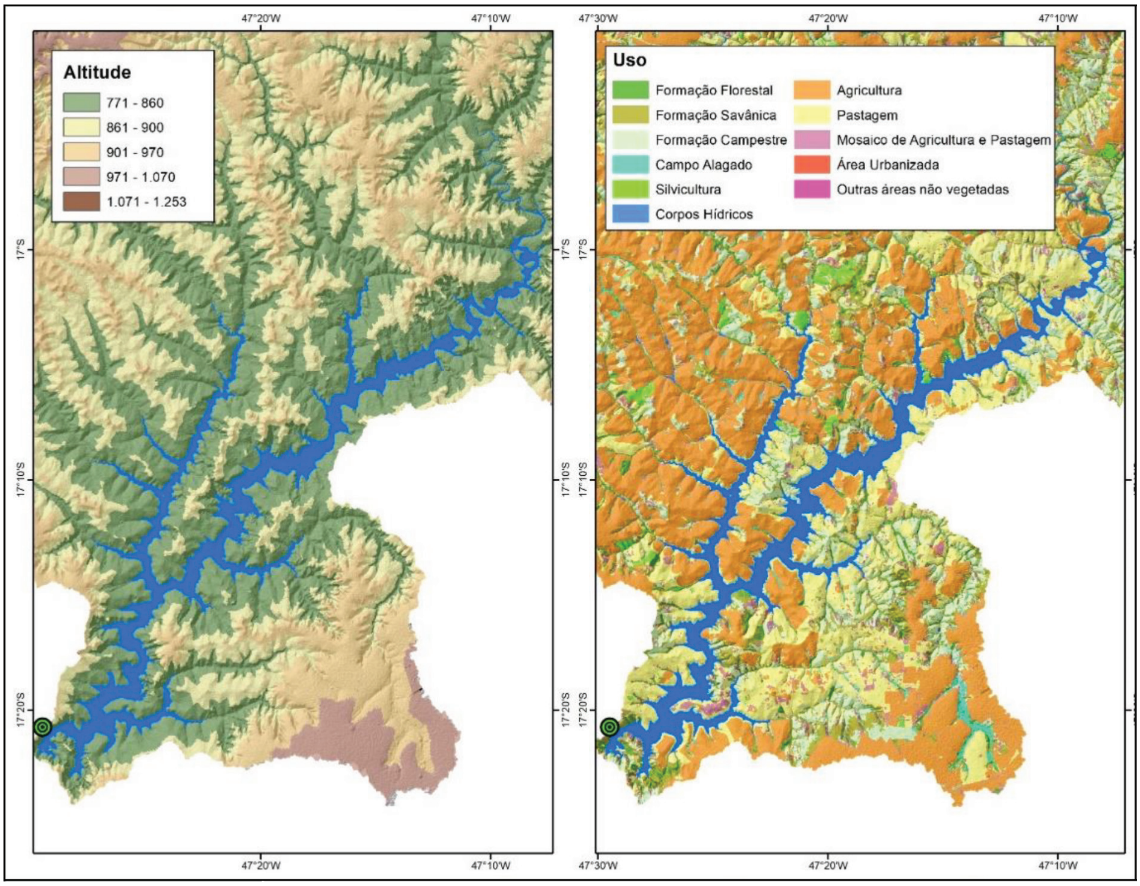
Possibly, other aspects that influence the erosive process should be considered in the case of UHE Batalha, such as, for example, the geological substrate and soil categories in the regional context. Thus, the present work is, above all, a preliminary analytical essay, which demonstrates the potentiality of using spectral indexes in the analysis and evaluation of sediment input in reservoirs of hydroelectric power plants, which must be validated and complemented by geoenvironmental attributes that explain their variability in time and space.

Conclusion

In the context of hydroelectric power plant reservoirs, a major concern is attributed to the contribution of sediments generated by erosive processes in the immediate surroundings, or in the hydrographic basin where the dam is located. This is because the transfer and deposition of sediments can cause silting of the reservoir, with the consequent loss of energy production capacity and reduction of the useful life of the hydroelectric enterprise[30, 31].

[30] Carvalho *et al.*, 2000.
[31] Cabral *et al.*, 2009.

Figure 6. Altimetry (in meters) and land use (2020) around the UHE Batalha reservoir



Source: SRTM and Mapbiomas (2021), org. authors.

In this work, by means of temporal and spatial changes in water reflectance caused by suspended sediments in the study areas, the potential for inferences about sediment inputs to reservoirs using remote sensing data and applying geoprocessing techniques to validate this information is investigated.

The use of orbital images to carry out these studies reduces associated costs, besides providing faster and consistent access to data, supporting the monitoring of the condition of suspended sediments in reservoirs. However, there is a need to validate the data estimated by the digital processing of satellite images with data collected in situ, in addition to the implementation of complementary data that can explain the spatial and temporal variability of water turbidity, especially data on precipitation and wind conditions, geological substrate and soil categories.

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