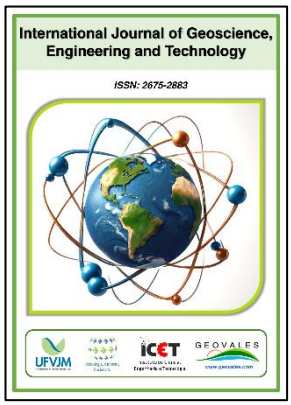
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Multitemporal analysis of the water surface of the Todos os Santos River Dam reservoir using remote sensing in the context of climate change

Ramon Gonçalves dos Santos[1], **Erica Karolina Barros de Oliveira**[1], **Jorge Luiz dos Santos Gomes**[1]

[1] Federal University of the Jequitinhonha and Mucuri Valleys, Teófilo Otoni, Brazil.

Email address
goncalves.ramon@ufvjm.edu.br (Ramon G. dos Santos) – Corresponding author.
erica.barros@ufvjm.edu.br (Erica K.B. de Oliveira)
jorge.gomes@ufvjm.edu.br (Jorge L.S. Gomes)

Abstract

Climate change is reshaping freshwater availability, particularly in semi-arid and water-stressed regions. The Vale do Mucuri, in northeastern Minas Gerais, Brazil, is increasingly affected, with part of its territory now included in the Brazilian semi-arid polygon. This study analyses the multitemporal variation in the water surface of the Todos os Santos River Dam reservoir in Teófilo Otoni (MG) from 2014 to 2024 and compares it with El Niño-Southern Oscillation (ENSO) phases. Landsat 8 dry-season images (June to September) were processed in QGIS using the Modified Normalized Difference Water Index (MNDWI), based on the green (B3) and shortwave infrared (B6) bands. Thresholded, vectorized water surfaces yielded annual reservoir areas, and temporal difference maps quantified retreat and expansion between consecutive years. ENSO phase and intensity were obtained from Ensemble ONI records. Water surface retreated in 2015, 2017, 2021 and 2024 and expanded in 2018, 2020 and 2023; the central reservoir remained stable, while shallower upstream arms varied most. Of the three El Niño years, only the super-intensity 2015 event coincided with retreat (–8.37 ha), whereas the weak (2018) and moderate (2023) events coincided with expansion, suggesting that local rainfall distribution and water consumption also influence variation. The absence of streamflow and rainfall series limited the analysis to qualitative correlation. Overall, MNDWI proved a low-cost, effective tool for monitoring small and medium-sized reservoirs, supporting water resource management in the Vale do Mucuri.

Keywords: MNDWI; geoprocessing; water resource management; spectral index; Landsat 8.

1. Introduction

Global climate change exerts profound effects on freshwater resources, altering water availability, water quality, and the ecological dynamics of rivers, lakes, reservoirs, and aquifers (Dahal, Bhattarai, Silwal, et al. 2025; Marengo 2008; Dordai, Roman, Roman, et al. 2026). In the face of global climate change, attention has increasingly turned to freshwater resources (Van Vliet, Jones, Flörke, et al. 2021), particularly to sectors dependent on potable water (Augusto, Gurgel, Câmara Neto, et al. 2012), such as agricultural production (Assad and Assad 2024) and public water supply (Brito Júnior 2025). Areas with poor rainfall distribution are especially affected (Angelotti, Fernandes Júnior and Sá 2012). Estimates indicate a water deficit exceeding 40% in some of the country's hydrographic regions by 2040 (ANA 2024), with the Vale do Mucuri region directly impacted by climate change, part of its territory having, in recent years, been incorporated into the Brazilian semi-arid polygon (Silva, Teixeira Marques, Rodrigues Queiroz, et al. 2026; Machado, Batista, Andrade, et al. 2026).

Climatic variations such as El Niño and La Niña directly affect rainfall distribution across Brazil (CPTEC 2026). Below-average cooling of the Pacific Ocean, associated with La Niña, can cause drought, increased rainfall, and regular precipitation in the South, North and Northeast, and

Southeast and Center-West regions, respectively (Chaves, Moura, Lima, et al. 2022). Conversely, El Niño is associated in these same regions with greater precipitation volumes, reduced rainfall, and irregular precipitation, driven by the warming of the Pacific (INMET 2024). These are known as ocean–atmosphere climatic phenomena associated with ENSO (El Niño–Southern Oscillation); this information is translated by tools such as the Oceanic Niño Index (ONI), which measures sea surface temperature (SST) anomalies in the Niño 3.4 region of the equatorial Pacific (INMET 2025).

The Vale do Mucuri region has a humid tropical, megathermal savanna climate, a climate type that presents problems of water scarcity, affecting the subsistence of the local population (Apolinário 2010). To alleviate water stress in such regions, several methods are employed, such as small dams (açudes) (Leonardo, Salgueiro, Almeida, et al. 2021), artificial water reservoirs built as barriers to retain rainwater and river flow (Sousa, Lira, De Oliveira, et al. 2022), intended for urban sanitation, animal management, agriculture and industry, electricity generation, as well as flood control (DNOCS 2023). However, such systems must be monitored to ensure proper use (MI 2002); in this regard, tools employing Geographic Information Systems (GIS) and geoprocessing can support the management and monitoring of watersheds and water bodies (Gomes, Vantil, Santos, et al. 2017).

From this perspective, the use of geoprocessing tools has become established as a relevant approach for obtaining practical solutions in spatial analysis (Farina 2006). Satellite imagery processed within a GIS environment enables spatial analyses that are more agile and consistent with the particularities of the territory under investigation (Câmara and Monteiro 2001). Accordingly, the integration of remote sensing and GIS, combined with geoprocessing techniques, can be applied to studies focused on the analysis of reservoir water surfaces (Silva, Calou and Silva 2023).

Furthermore, in geoprocessing, several spectral indices have been applied to the study of water bodies, including the Modified Normalized Difference Water Index – MNDWI (Xu 2006). This index is widely used in remote sensing for the identification, delineation, and monitoring of water surfaces from satellite imagery, as it exploits the characteristic spectral behavior of water across different bands of the electromagnetic spectrum, being particularly effective at suppressing other land surface targets when compared to other indices (Gil, Padovani and Coelho 2019). Thus, this index constitutes a relevant tool in environmental and hydrological studies, particularly in analyses of spatial dynamics, temporal variation, and water resource management (Casado and Araújo 2024).

In this context, the present study aims to compare the water surface area with the El Niño and La Niña (ENSO) climatic phenomena of the Todos os Santos River Dam reservoir, located in the municipality of Teófilo Otoni, in the state of Minas Gerais, Brazil, using Landsat 8 satellite imagery over the period 2014–2024, through the application of the MNDWI index.

2 Material and Methods

2.1 Study area characterization

The municipality of Teófilo Otoni is located in the northeastern region of the state of Minas Gerais (Ferraz, Valadão, Almeida, et al. 2017; Gomes 2020) with a population of 137,418 people (IBGE 2022). Moreover, its main watercourse, the River Todos os Santos, originates in the locality of Poté, with an average length of 172 km and a mean annual discharge of 700 L/s. The damming of the river's flow was planned for reasons of flow regularisation, protection against flood seasons, and water supply to the population during periods of drought; the dam is located 15 km from the urban area (Costa, Silva and Colares 2019; Durães, Guimarães, Rocha, et al. 2021), at the coordinates Lat: -17.858918° and Long: -41.571414°. Completed in 2012, the structure created a flooded area of 128 hectares (Almeida, Barbosa, Almeida, et al. 2019). With a length of 196 meters and a height of 33 meters, the dam has a storage capacity of 12 billion liters of water (Lopes 2012). Figure (1) shows the location of the Todos os Santos River Dam, along with the water body polygon from IDE-Sisema (Minas Gerais 2026) that delimits the reservoir.

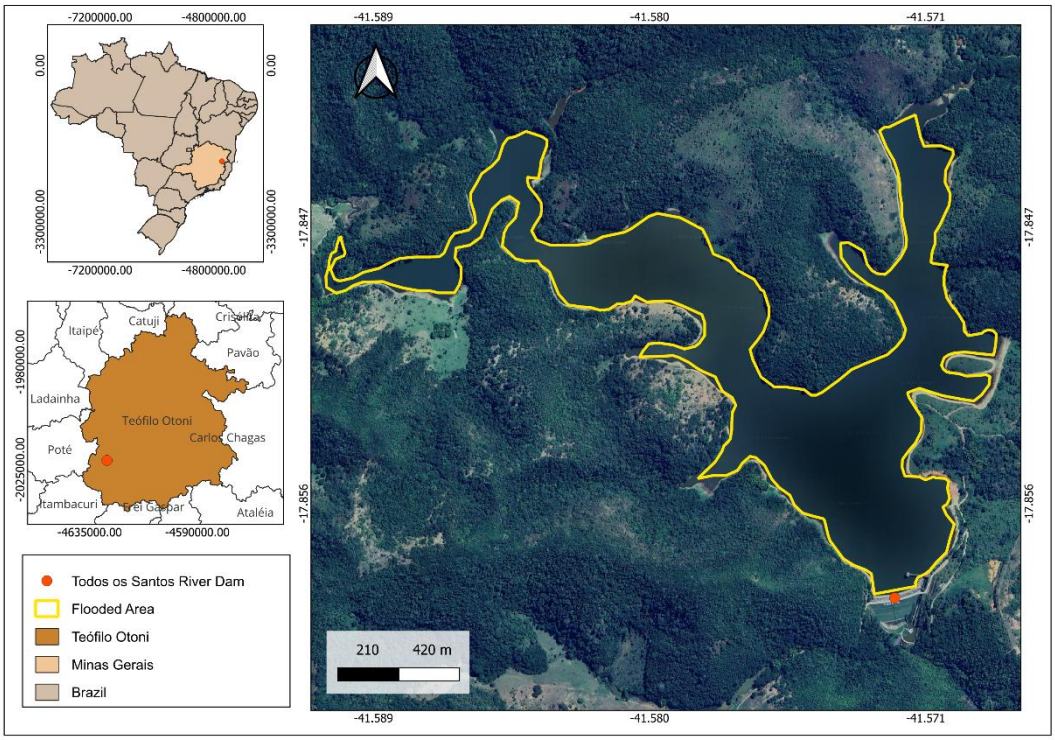


Figure 1 – Location map of the River Todos os Santos Dam in the municipality of Teófilo Otoni, Brazil.

Furthermore, Martins (2010) considers the regional climate, at least for the Mucuri River Basin, as humid tropical, with well-defined summer and winter seasons and an average rainfall of 1009 mm per year (Ferraz, Valadão, Pinto, et al. 2022), concentrated in the rainy season (Almeida, Pereira, Pinto, et al. 2020), which extends from October to March and in which approximately 80% of the total annual precipitation occurs (Ferraz 2019). Moreover, these rainfall seasonal patterns were also identified in the Minas Gerais portion of the Atlântico Leste Hydrographic Region by Oliveira et al. (2025), that analysed precipitation data from 33 stations between 1980 and 2022.

2.2 Modified Normalized Difference Water Index – MNDWI

The spatial data used in this study to calculate the MNDWI were obtained using the Python programming language in the Jupyter Notebook software, through which Landsat-8 satellite images were exported, and the raster product consisted of the Green Band (B3) and the Short-Wave Infrared Band (B6), with a spatial resolution of 30 meters and cloud filtering set at 10%. The images downloaded correspond to the years 2014, 2015, 2017, 2018, 2020, 2021, 2023, and 2024, from the dry-season months of the Teófilo Otoni region, which range from June to September, with June covering the years 2017, 2020, and 2021. The 2023 image fell in July, August covered 2014, and September covered the years 2015, 2018, and 2024.

The MNDWI proposed by Xu (2006) produces, as its final output, an image with values ranging from 1 (water) to 0 and –1 (non-water); see Equation (1).

$$MNDWI = \rho green - \rho swir / \rho green + \rho swir \qquad (1)$$

Thus, ρgreen (Band 3) corresponds to the green band, and ρSWIR (Band 6) corresponds to the Short-Wave Infrared band. With these spectral bands in hand, the next step was to calculate the MNDWI in the Geographic Information System software QGIS, version 3.34.9; the reservoir was highlighted using the raster calculator, applying Eq. (1), after which the indices were generated for each year.

Subsequently, the next step was to calculate the threshold using the code expression "MNDWI layer > 0" entered into the raster calculator, highlighting all pixels with values above zero and leaving all remaining pixels black; this method was adopted as the classification criterion, based on the literature (Ji, Zhang and Wylie 2009; Ali, Cheema, Waqas, et al. 2021; McFeeters 1996), and a visual inspection was eventually carried out to verify the coherence of the classification. The second step was polygonization, converting the raster to a polygon,

performed in QGIS through the following sequence: Raster, Conversion, Raster to Polygon. Once the flooded-area polygon was obtained, the reservoir area was calculated using the field calculator in the attribute table, applying the command "$area/10,000," yielding the area in hectares. A polygon of the study site was then created to clip the entire image, in order to exclude other water bodies surrounding the study area and focusing solely on the water reservoir surface.

Afterward, using the clipped threshold images, the following step was to compute the difference through the raster calculator, that is, the subtraction of one image from another, with the most recent image minus the oldest, resulting in an image that shows the retreat and expansion of the reservoir's water surface over the years. The flooded area, along with retreat and expansion, was then calculated using the r.report tool from the GRASS GIS plugin. It was sufficient to configure it using a difference layer, generating a file with information on positive, negative, and zero values. The positive value represents an area that had no water in the oldest year but had water in the most recent year, the negative value represents an area that had water in the most recent year, and zero represents an area where the flooded area underwent no change. Subsequently, the positive values were subtracted from the negative values to determine whether there was retreat or expansion in that year, the net balance, and Table (3) (in the results section) was constructed on this basis.

2.3 El Niño–Southern Oscillation (ENSO)

Data acquisition was carried out by evaluating information available on the Webber Weather website (Webb 2026), specifically the List of ENSO Event Phases and Peak Intensity (1850 to 2024). Moreover, the years chosen range from 2014 to 2024 because El Niño and La Niña seasons do not follow fixed dates and can span more than one year (Chen, Du and Zhang 2025; Lu, Schultze, Carré, et al. 2025). Thus, the ENSO data cover the years selected for the water surface analysis. The website itself offers a table linking months and years to their respective average temperatures, titled the Ensemble Oceanic Niño Index (ENS ONI), and another table showing temperature ranges and the intensities to which they fall, titled the Ensemble ONI ENSO Event Peak Intensity Table (1850 to 2026). With the dates of the images used in this study in hand, Table (2) was compiled.

The flowchart (Figure 2) schematizes the Material and Methods section, focusing on subsections 2.2 and 2.3, the Modified Normalized Difference Water Index (MNDWI) and El Niño–Southern Oscillation (ENSO), respectively.

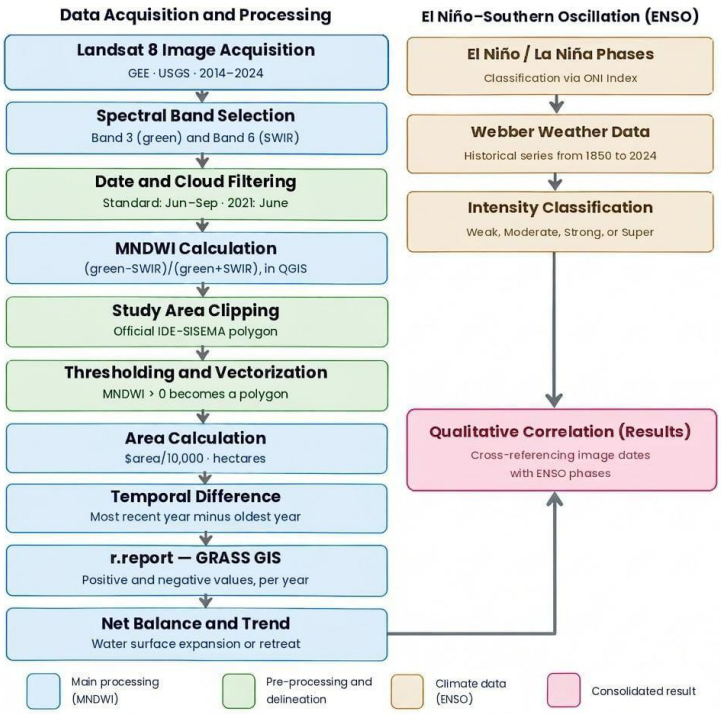


Figure 2 – Flowchart structuring the Material and Methods section, subsections 2.2 and 2.3.

3. Results and Discussion

For the years 2015, 2017, 2021, and 2024, there was a retreat in the water surface of the Todos os Santos River Dam, while in the years 2018, 2020, and 2023 the reservoir showed expansion. The central part of the reservoir remained relatively stable throughout the series, while the section near the shallower edge showed greater variability. Figure (3) presents the final MNDWI result obtained in QGIS.

Figure (4) clearly shows the retreat and expansion of the water body for each year, calculated using the Modified Normalized Difference Water Index (MNDWI) images. Blue areas indicate expansion of the water surface, and red areas indicate its retreat.

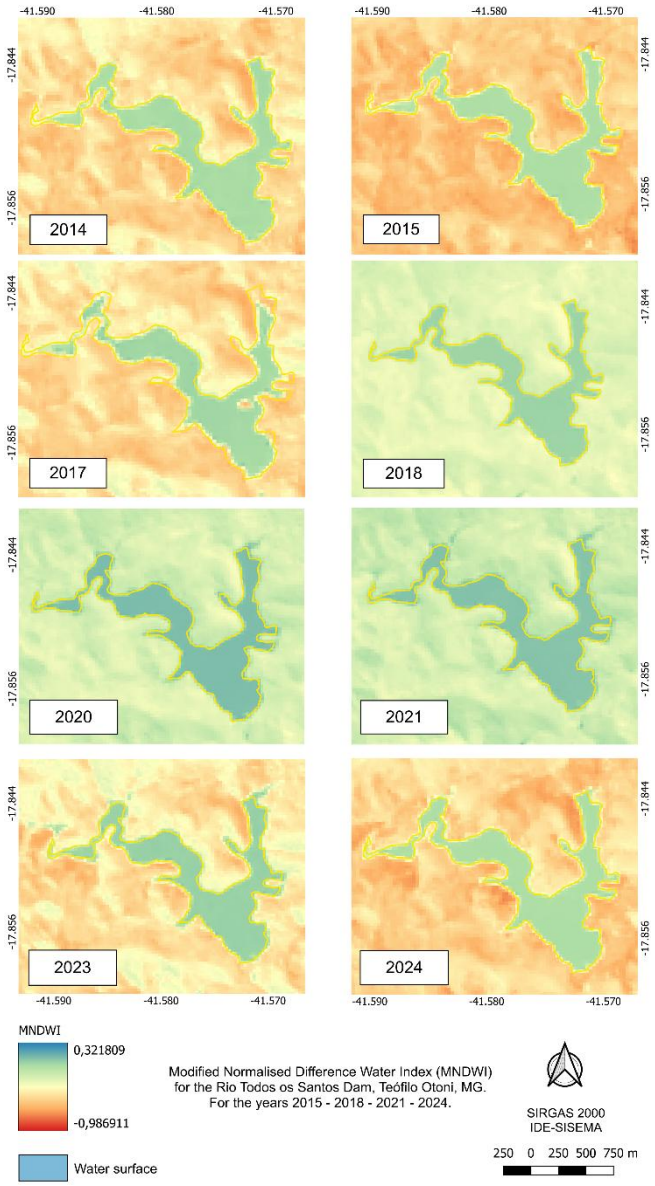


Figure 3 – Evolution of the Modified Normalized Difference Water Index (MNDWI) for the Todos os Santos River Dam, for the years 2014, 2015, 2017, 2018, 2020, 2021, 2023, and 2024

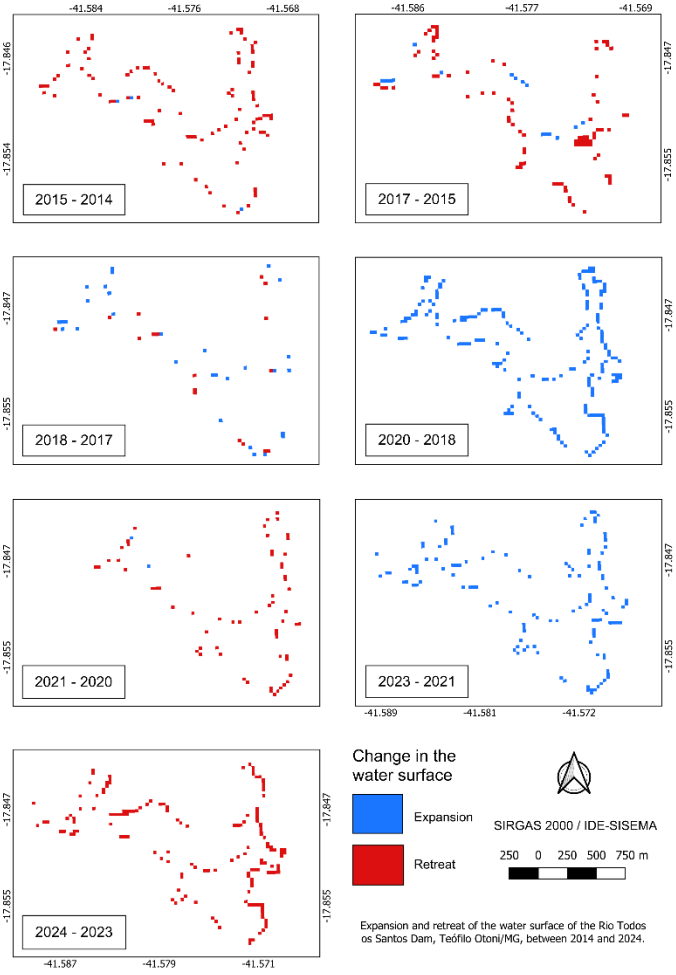


Figure 4 – Water surface expansion and retreat of the Todos os Santos River Dam for the years 2014, 2015, 2017, 2018, 2020, 2021, 2023, and 2024

Based on an analysis of the two Webber Weather (Webb 2026) tables and knowing the dates of the images used in this study (Table 1), Table (2) was compiled. On 25 September 2015, El Niño was active, and its intensity was classified as Super El Niño. On 1 September 2018, El Niño was Weak, and on 13 July 2023, El Niño was categorized as Moderate. It is observed that La Niña was not active on any of the image dates used in this article, and both phenomena were inactive in the years 2014,

2017, 2020, 2021, and 2024, which may indicate that factors such as rainfall distribution and local water consumption also influence the results (see the Table 1 and 2).

Comparing the retreat and expansion values for each year with the information on El Niño activity and intensity, it is observed that, in 2015, El Niño exerted an influence, since there was a loss of 8.37 hectares of water surface, as this phenomenon influences the Southeast Region, where the city of Teófilo Otoni is located, with irregular rainfall. In 2018, the phenomenon had no influence over the reservoir's water surface retreat, since there was an expansion of 1.17 hectares; this contrast is expected, as weak events tend to produce more discrete SST anomalies in the Niño 3.4 region and consequently result in weaker atmospheric responses (Wolter and Timlin 2011). The same occurred in 2023, when the phenomenon had no discernible influence, with the calculated area showing a gain of 11.07 hectares of water, even though the event was classified as Moderate. This may be because the 2015 El Niño event was super intense, so its influence on the Teófilo Otoni region may have been more significant than that of the other two classifications.

Moreover, Table (3) presents the positive and negative values for each year covered in this article, the net balance (the difference between positive and negative values), and the retreat or expansion trend. Additionally, Figure (5) emphasizes the comparison between the MNDWI and the retreat and expansion areas of the Todos os Santos River Dam.

Table 1 – Landsat 8 satellite image dates for the years 2014, 2015, 2017, 2018, 2020, 2021, 2023, and 2024.

Date	Hour
05/08/2014	09:50:24
25/09/2015	09:50:23
10/06/2017	09:50:04
01/09/2018	09:49:57
02/06/2020	09:49:55
21/06/2021	09:50:16
13/07/2023	09:50:06
17/09/2024	09:50:20

Table 2 – Classification of ENSO phases and maximum intensity observed (2014, 2015, 2017, 2018, 2020, 2021, 2023, 2024).

Year	Month	ENSO	Intensity
2014	August	No influence	-
2015	September	El Niño	Super
2017	June	No influence	-
2018	September	El Niño	Weak
2020	June	No influence	-
2021	June	No influence	-
2023	July	El Niño	Moderate
2024	September	No influence	-

Table 3 – Negative and positive values, and calculation of retreat and expansion.

Year	Positive value (ha)	Negative value (ha)	Net balance (ha)	Trend
2015-2014	0,27	8,64	-8,37	Retreat
2017-2015	1,44	7,83	-6,39	Retreat
2018-2017	2,7	1,53	1,17	Expansion
2020-2018	16,65	0	16,55	Expansion
2021-2020	0,18	5,67	-5,49	Retreat
2023-2021	11,07	0	11,07	Expansion
2024-2023	0	13,59	-13,59	Retreat

Regarding limitations, the study lacks access to actual reservoir volume data or rainfall time series for each image date, which prevents establishing a causal relationship between ENSO and variations in the water surface of the Todos os Santos River Dam, thereby restricting the analysis to a qualitative correlation. Even so, the MNDWI proved to be a low-cost and effective tool for multitemporal monitoring of the reservoir, correctly identifying retreat in two of the three years under El Niño influence.

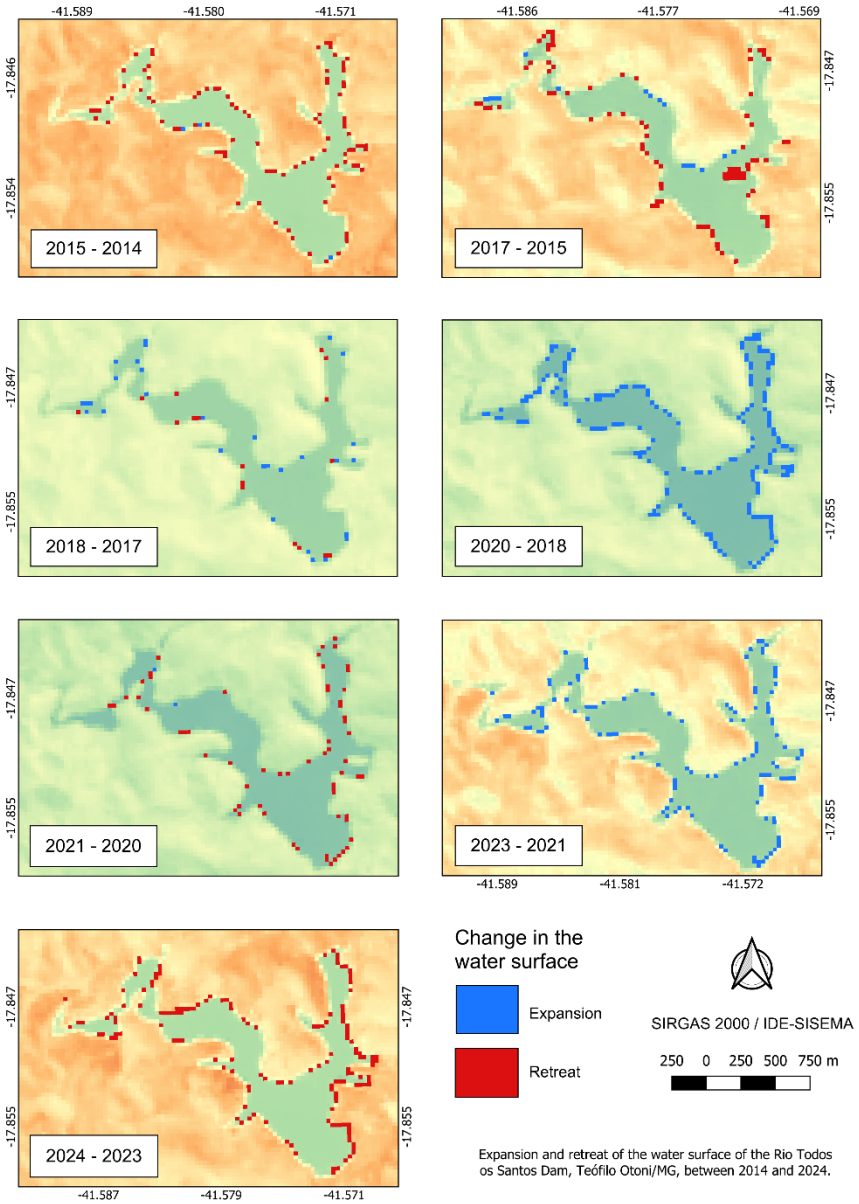


Figure 5 – Expansion and retreat contextualized with the NDWI index of the Todos os Santos River Dam (2014, 2015, 2017, 2018, 2020, 2021, 2023, 2024.

4. Conclusion

The present study aimed to analyse the temporal variation of the water surface of the Todos os Santos River Dam, in Teófilo Otoni, between 2014 and 2024, using the MNDWI applied to Landsat 8 images, correlating the results with ENSO phases (La Niña and El Niño) over the same period. Water surface retreat was identified in 2015, 2017, 2021, and 2024, and expansion in 2018, 2020, and 2023, with most of the variation concentrated in the shallower upstream tributary arms of the reservoir, while its central portion remained stable throughout the entire series.

Of the three years under El Niño influence (2015, 2018, and 2023), one showed retreat (2015), consistent with the pattern of irregular rainfall that the phenomenon typically brings to the Southeast Region; the exceptions were 2018 and 2023, under weak and moderate intensity El Niño events, which showed expansion instead. The remaining years, with no El Niño or La Niña activity, indicate that other factors, such as the distribution of rainfall within the year itself and local water consumption, also influence the reservoir's behaviour.

The MNDWI was confirmed as a low-cost method with adequate precision for the multitemporal monitoring of small and medium-sized reservoirs, and the results obtained can support the monitoring of the Todos os Santos River Dam and assist water management agencies in the Mucuri Valley region.

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