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Comparison Between Three Methods to Monitor Reservoir Extension in the Brazilian Semi-Arid Region

Comparação entre Três Métodos de Monitoramento da Extensão de Reservatórios no Semiárido Brasileiro

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Abstract

The State of Pernambuco covers an extensive semi-arid area where the Caatinga biome dominates. This region is characterized by long periods of drought, highlighting the need for water resource optimization. This paper aimed to compare three methods to assess reservoir changes: MapBiomas' products, the Normalized Difference Water Index (NDWI), and a support vector machine (SVM) algorithm. Initially, we obtained the monthly precipitation from 1987 to 2019 and calculated the yearly accumulation. Mapbiomas, Landsat 7 ETM, and Landsat 8 OLI data from 2012-2018 were accessed and processed using the Google Earth Engine platform. We obtained the annual image with the median pixel criterion to determine the NDWI and quantify the annual reservoir area. For the supervised classification with SVM, samples from different land-use types of the study area were used to train the algorithm. From 2012 to 2018, a reservoir reduction of 63.42% was observed with MapBiomas images, 69.49% with NDWI images, and 67.69% using the SVM algorithm. The results obtained using NDWI were the most similar to those from the artificial intelligence classification, indicating that NDWI can be used to monitor the reservoir conditions.

Keywords: Landsat; Google Earth Engine; Water resources

Resumo

O estado de Pernambuco cobre uma extensa área semi-árida, onde domina o bioma Caatinga. Essa região é caracterizada por longos períodos de seca, destacando a necessidade de otimização dos recursos hídricos. Este estudo teve como objetivo comparar três métodos de identificação de cobertura de água em reservatório: dados do MapBiomas, o Índice de Água de Diferença Normalizada (NDWI) e um algoritmo de máquina vetorial de suporte (SVM). Inicialmente, obtivemos a precipitação mensal de 1987 a 2019 e calculamos o acumulado anual. A plataforma do Google Earth Engine permitiu o acesso aos dados do Mapbiomas, Landsat 7 ETM, e Landsat 8 OLI de 2012-2018 e desenvolveu o processamento de imagens. Obtivemos a imagem anual com o critério do pixel mediano para determinar o NDWI e quantificar a área anual do reservatório. Para classificação supervisionada com SVM, amostras dos diferentes tipos de uso da terra da área de estudo permitiram treinar o algoritmo. De 2012 a 2018, foi observada uma redução de reservatório de 63,42% com base nas imagens MapBiomas, 69,49% com imagens NDWI e 67,69% usando o algoritmo SVM. Os resultados obtidos com o NDWI foram próximos aos da classificação de inteligência artificial, indicando que o NDWI pode ser utilizado no monitoramento do reservatório ao longo do ano.

Palavras-chave: Landsat; Google Earth Engine; Recursos hídricos

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1 Introduction

In the semi-arid regions of Brazil, the irregularity and low volume of rainfall associated with high radiation incidence and high temperatures limit the availability of water (Silva et al. 2010). These conditions can be enhanced due to climate change, which is expected to increase the temperature further and reduce the rainfall volume, which will hinder water supply management in these areas. Understanding the hydric response to atmospheric changes can assist water resource management, prioritizing rational and sustainable water usage (Pinto & Centeno 2016).

Technological advances and innovations in computer science for gathering information about surface coverage have made it possible to rapidly identify landscape physiognomies, with a high frequency of observations. Artificial intelligence (AI) techniques have been used to solve real problems, building upon their initial purely theoretical applications (Faceli et al. 2011).

There are several AI methods, and machine learning algorithms are one of the most used to perform regression and classification, allowing the comparison between several variables (Lary et al. 2016). Thus, the support vector machine (SVM) algorithm is advantageous due to its application and the degree of data adjustment, corresponding to the primary hydric monitoring tool from the orbital data. This technique is especially relevant in areas with long drought periods and different degrees of spectral information. There has been no previous report of this technique being applied to reservoirs in the Pernambuco semi-arid region.

Traditionally, mapping of land use, land cover, and water resources in these regions has been conducted using remote sensing techniques, which became an essential instrument for studying the physical environment (Oliveira, Acorsi & Smaniotto 2018). Different satellite sets have become essential in water resources monitoring studies, especially the Landsat sets. Dos Anjos et al. (2017) applied the NDWI technique to a reservoir in Paraiba, Brazil, for semi-arid regions. This study detected a reduction in reservoir levels due to a drought in the region between 2009 and 2016. In contrast, Martins et al. (2019) analyzed a reservoir in the city of Sobradinho, Brazil, using a combination of data from Landsat 8 and Tropical Rainfall Measuring Mission (TRMM) along with turbidity data to evaluate changes in the reservoir area and turbidity variability within the reservoir during the recent drought (2012–2017). They found a reduction of 62.77% in the water surface of the Sobradinho reservoir.

It is worth mentioning the initiative by the Brazilian Annual Land Use and Land Cover Mapping Project, MapBiomas, which supplies annual land use and land cover images to Google Earth along with Landsat data (Pereira Costa et al. 2018). Similar initiatives using the Google Earth platform have been developed in other regions of the world, such as in Peru (Villavicencio et al. 2018) and Mozambique (Oliveira, Acorsi & Smaniotto 2018), with good results for identifying the land use and vegetation type, and the native vegetation of these environments.

The present study investigates changes in water surface of the reservoir Serrinha II, located in the municipality of Serra Talhada. A comparative analysis between MapBiomas, NDWI, and SVM data is utilized to identify and quantify the water surface, which is essential for understanding the sensitivity of this reservoir to environmental changes.

2 Methodology and Data

2.1 Study area

The Serrinha II reservoir is located in the watershed of the Pajeú River, in the municipality of Serra Talhada, in the state of Pernambuco, Brazil (8º0’58” S and 38º31’21” W; Figure 1). It was built and operated by the National Department of Construction to Combat Drought and had a maximum cumulative capacity of 3,000,000 m³ (Rocha 2018).

The climate is typical of the semi-arid region, which is hot and dry (Bsh), with an average rainfall of 657 mm year^{-1}, an average annual temperature of 25.8 °C, and high evaporation (Alvares et al. 2013; Cruz Neto et al. 2017; Rossiter et al. 2020).

2.2 Data Acquisition and Processing

The Pernambuco water and climate agency (APAC) has made monthly precipitation level data available from a station located in Serra Talhada between 1987-2019. These data were accumulated by year for comparison with the satellite images.

The Landsat image layers were generated on the Google Earth Engine platform using the collection of reflectance data from Landsat 7 Enhanced Thematic Mapper (ETM) and Landsat 8 Operational Land Imager (OLI). The Landsat products have a temporal resolution of 16 days and a spatial resolution of 30 meters. Three methods for identifying water coverage were considered using this database, as described in the following sections.

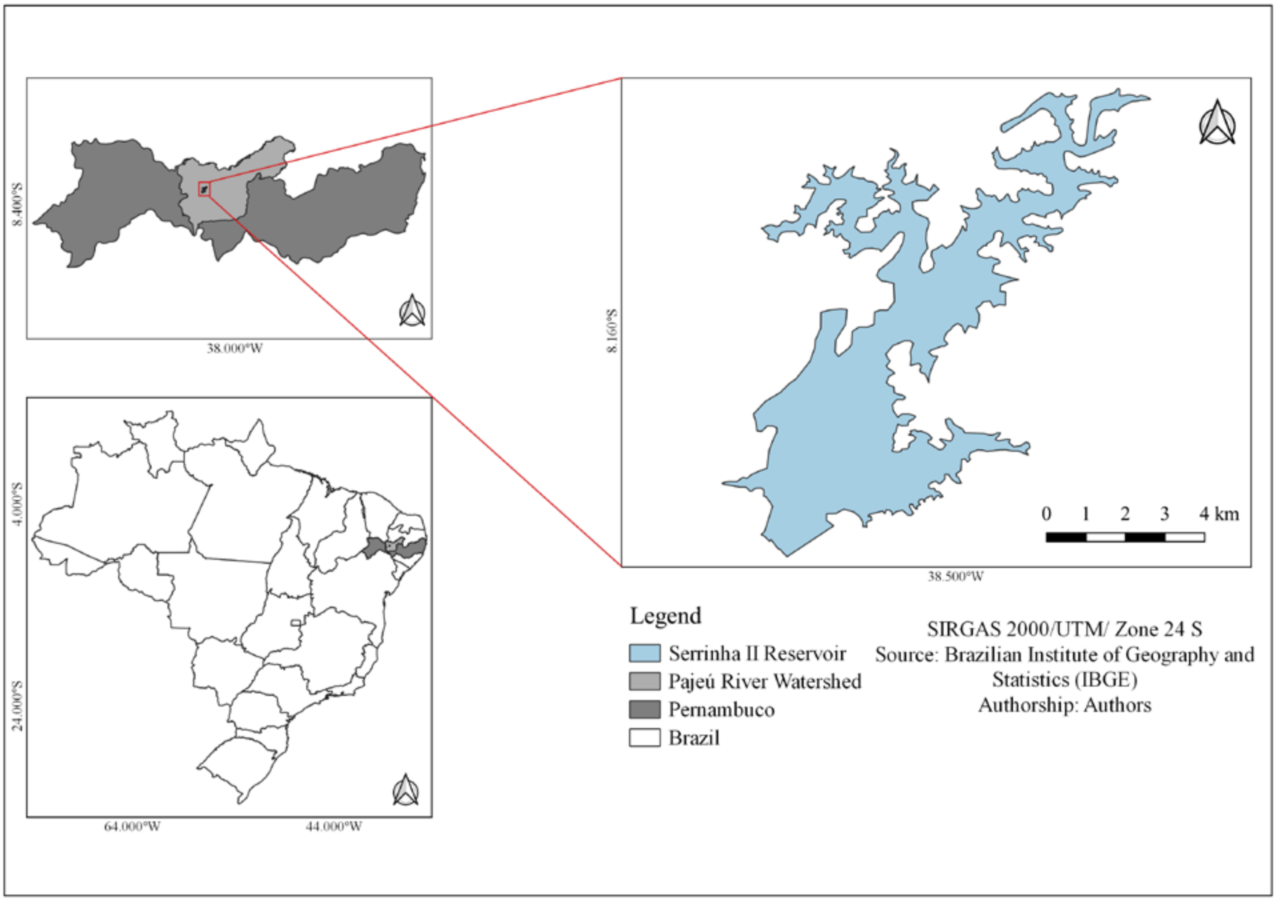

Figure 1 Location of the Serrinha II reservoir in the Pajeú River basin, Pernambuco – Brazil.

After obtaining the classified scenes, they were taken to QGIS (2019) (3.10) for clipping in the study area, counting the water coverage area with the r.report tool, and preparing thematic maps, as demonstrated in Figure 2.

2.3 Reservoir Area Identification Methods

2.3.1. Mapbiomas Data

Digital processing of the satellite images utilized data acquired from the MapBiomas platform for vegetation coverage and land use in the municipality of Serra Talhada. The data were accessed using the Google Earth Engine platform, and we obtained the product images from Mapbiomas' "collection 6" from 2012 to 2018 (Projeto Mapbiomas 2022). It is noteworthy that "collection 6" is a product of Mabiomas that covers the period 1985-2020 and shows improvements in classification from the application of random forest. Products are shown as annual averages and have a resolution of 30 meters since they are derived from Landsat.

MapBiomas data was used for comparison as it corresponds to data made available annually on large-scale land use and land cover thematic map. However, it is necessary to evaluate the precision in identifying water resources by verifying which methodological approach best describes the field variability, especially in the Brazilian semi-arid region.

2.3.2. Determination of NDWI

The NDWI can differentiate between water, soil, and vegetation (McFeeters 1996). Pereira, Lohmann and Maganhotto (2016) pointed out the efficiency and objectivity of the water index for classifying and mapping water bodies, thereby reducing the operator's subjectivity. It assigns values between -1 and +1, with negative index values (< 0) associated with exposed soil or vegetation and positive index values for water (> 0). This index, as described in Equation 1, uses two spectral bands, one corresponding to the visible green electromagnetic spectrum and the other near-infrared.

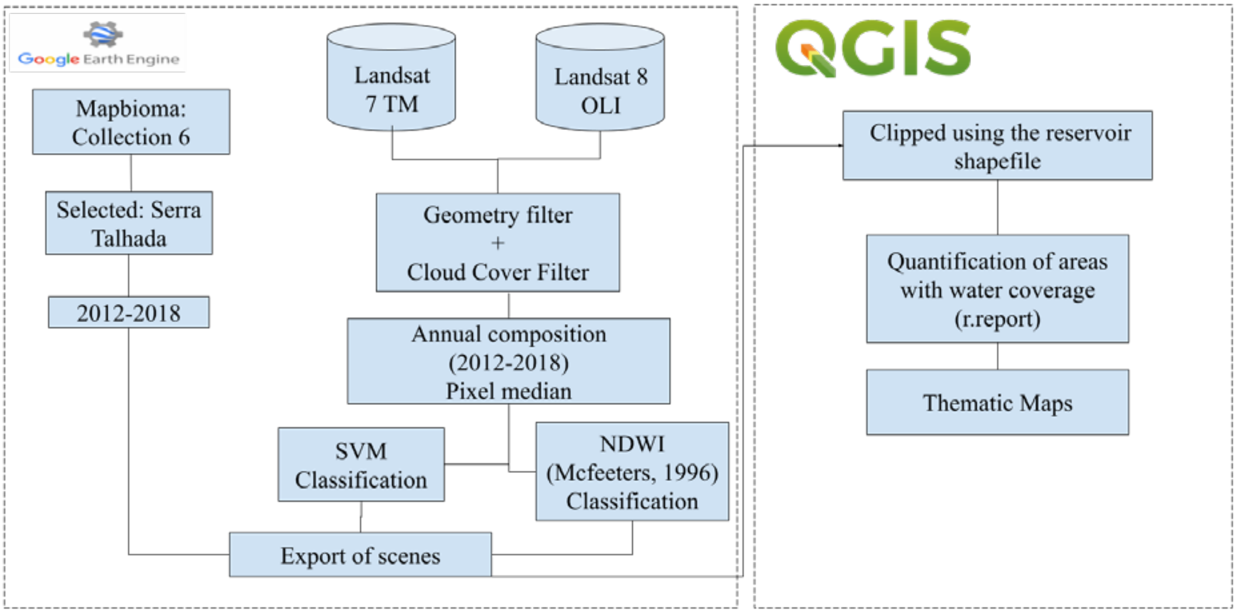

Figure 2 General scheme of the methodology.

$$NDWI= \frac{(\rho G - \rho NIR)}{(\rho G + \rho NIR)} \quad \textbf{(1)}$$

where: ρG is the reflectance in the green band, corresponds to band two (0.52 - 0.60 μm) on Landsat 7 and band three (0.53 - 0.59 μm) on Landsat 8, and ρNIR is the reflectance in the near-infrared band, corresponds to band four (0.77 - 0.90 μm) on Landsat 7 and band five (0.85 - 0.88 μm) on Landsat 8.

We use the available daily images to calculate an annual image based on a selection criterion: maximum cloud cover of 50% and median pixel. The annual composition was calculated using the pixel median, and after the annual image was obtained, we estimated the NDWI. We emphasize that this processing occurred on the Google Earth Engine (GEE) platform.

2.3.3. Training of the Machine Learning Algorithm

The machine learning algorithm SVM was used for supervised classification of the study area based on Landsat 7/ETM+ and Landsat 8/OLI annual images, as presented in section 2.3.1, due to promising results expressed by this technique for identifying physiognomies (Alba 2020; Wolfer et al. 2020). Thus, this technique uses a supervised classification in the present study, aiming at controlling the sampling and ensuring adequate methods for comparing the results. Sampling of the different land uses was determined for each year, corresponding to the data set for the algorithm.

The radial type of kernel was used for training, while a cost value (C) of 1 responded better to the data. The other sets of algorithm adjustments were set up in variable mode to represent better the peculiarities of every year observed.

The classification validation obtained by the AI techniques was done by observing the coefficient values Kappa e global accuracy (Equations 2 and 3). The supervised classification of the orbital images and their validation were developed with Google Earth Engine.

$$k= \frac{(n^* \sum_{i=1}^{r} x_{ij}) - \sum_{i=1}^{r} (x_i^* x_j)}{n^2 - \sum_{i=1}^{r} (x_i^* x_j)} \quad \textbf{(2)}$$

$$G= \frac{A}{n} * 100 \ (3) \quad \textbf{(3)}$$

where: K = Kappa accuracy index; r = number of rows in the matrix; xii = number of observations in row [i] and column[i]; xi+ and x+i = total marginal row[i] and column[i]; n = total number of observations respectively; G = global accuracy; A = sample points with success.

3 Results

Local precipitation was highly variable, with the highest rates occurring between January and April (Figure 3A). After the drought period from 2012 to 2017

(Silva et al. 2017), precipitation in 2017 and 2018 was closer to the average precipitation for the location, 643 mm per year from 1987 to 2019 (Figure 3B). 2012 presented the lowest precipitation rate during the study period (2012–2018) and an annual total of approximately 200 mm.

Spatial data facilitate the mapping and identification of land use dynamics throughout the study period. Figure 4 shows the Serrinha II reservoir temporal changes using the data obtained from MapBiomas, highlighting the reduction of the reservoir until 2017. The reservoir area showed a 63.42% decrease from 2012 to 2018.

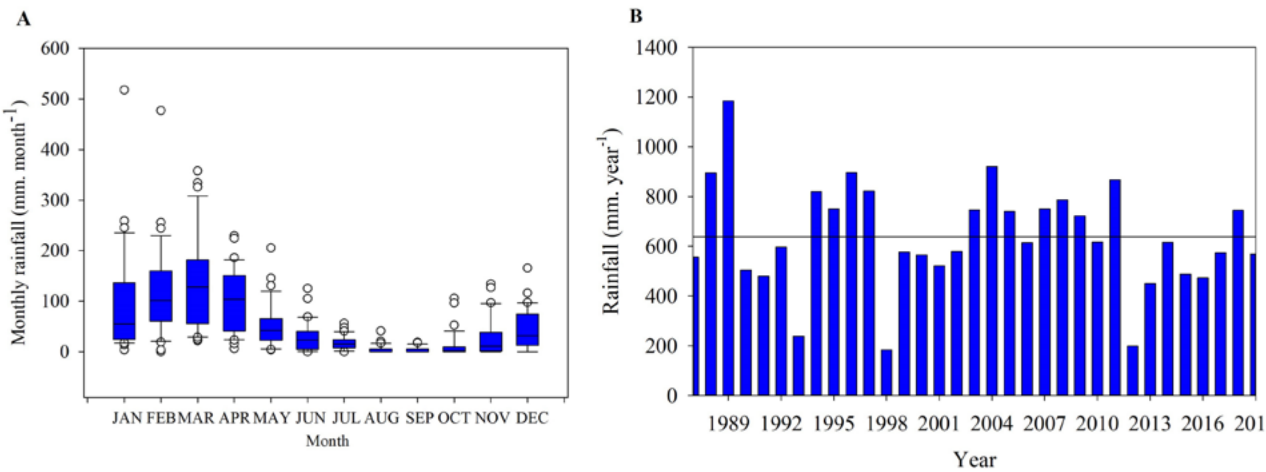

Figure 3 Annual precipitation (mm) in the municipality of Serra Talhada from 1987 to 2019: A. box plot of monthly precipitation; B. annual accumulated precipitation and the black line is the annual average. Source: APAC.

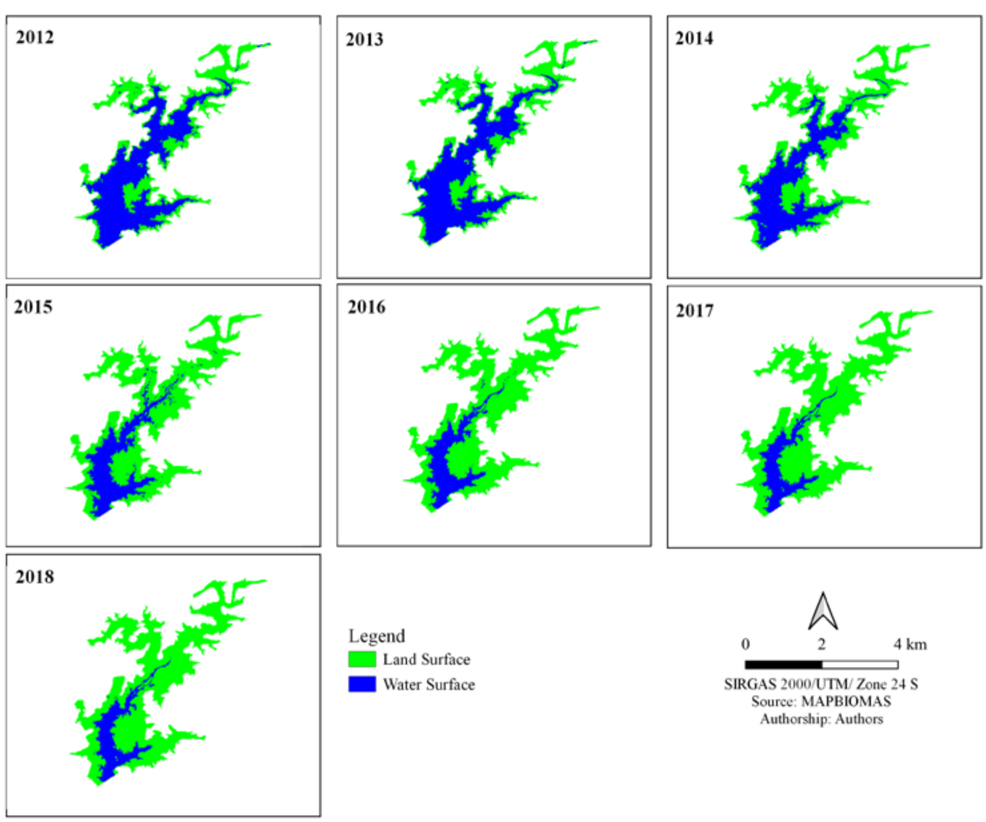

Figure 4 Map of land use and land cover in the reservoir Serrinha II, Pernambuco, from 2012 to 2018, obtained by MapBiomas.

Landsat images, classified with the NDWI technique, identified the reservoir's water and land surface, allowing the quantification of reservoir extent (Figure 5). The NDWI presented a similar performance to Mapbiomas (Figure 4), showing the reduction in the reservoir area from 2012 to 2017 and increasing in 2018. Overall, the reservoir area decreased 69.49% between 2012 and 2018.

Maps using the SVM algorithm identify different land-use classes and cover and their dynamics throughout the study period (Figure 6). Similar to the others methods, the SVM algorithm shows a reservoir area reduction of 67.69% between 2012 and 2018.

When analyzing the quality of the classification using AI (SVM algorithm), the results were found to be acceptable, with the annual Kappa coefficient found to be > 0.60 during the validation process (Table 1). The accuracy and kappa values were lower in the dry years, indicating more significant confusion in separating thematic classes by the machine learning classifier SVM.

Table 2 compares the methods and the NDWI - MapBiomas relationship with an average difference of 271.46 ha, with a coefficient of 15% ($r^2 = 0.99$). On the other hand, the NDWI-SVM relationship showed similar NDWI - MapBiomas, with an average difference of 260.94 ha and CV of 44.67%. The reservoir areas calculated for each method (MapBiomas and NDWI) showed high conformity with those obtained using the SVM algorithm ($r^2 > 0.96$). However, the Mapbiomas-SVM results showed a minor difference - mean 10.53 ha- and a more considerable variation - CV 945%.

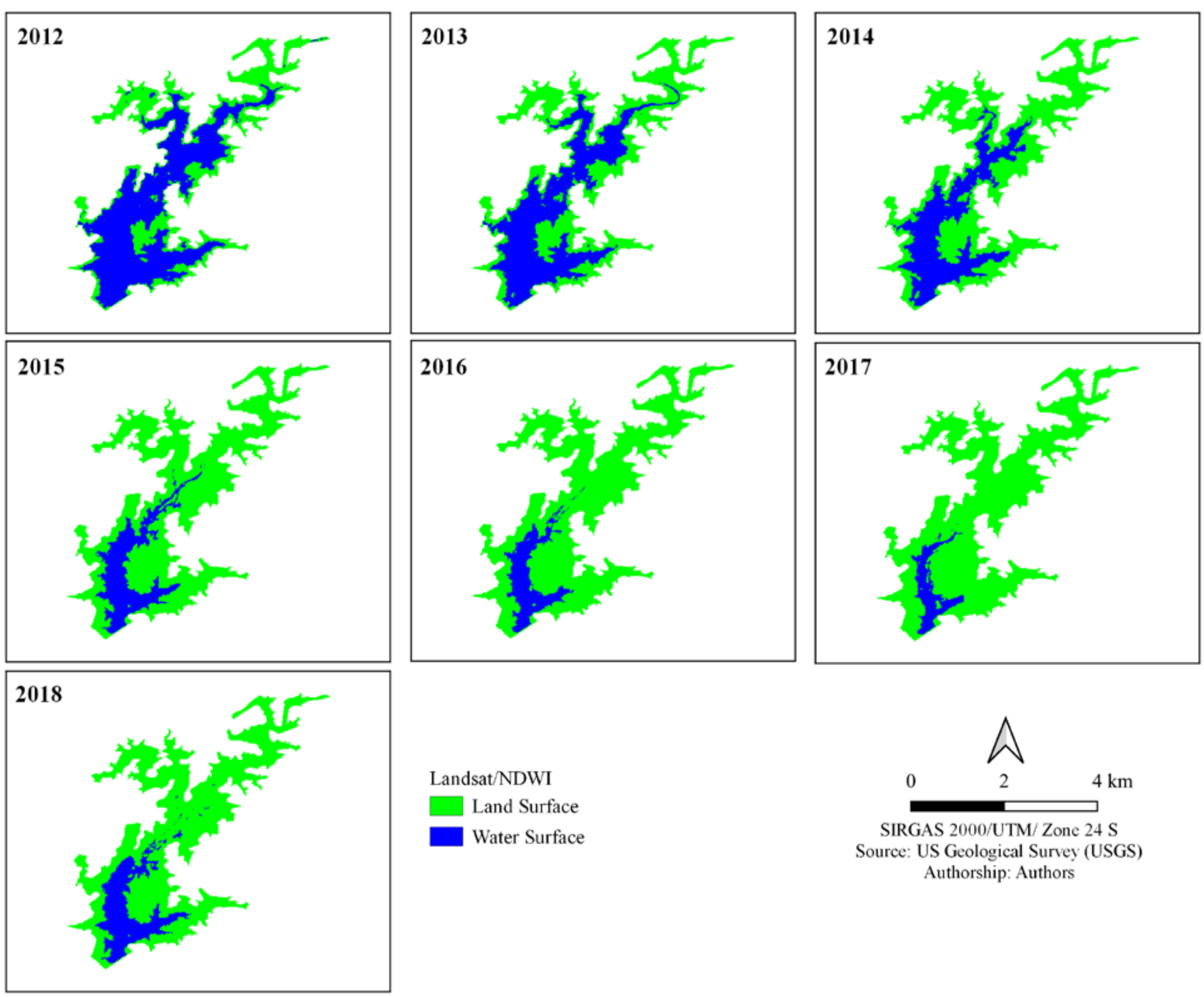

Figure 5 NDWI maps of the Serrinha II reservoir, from 2012 to 2018.

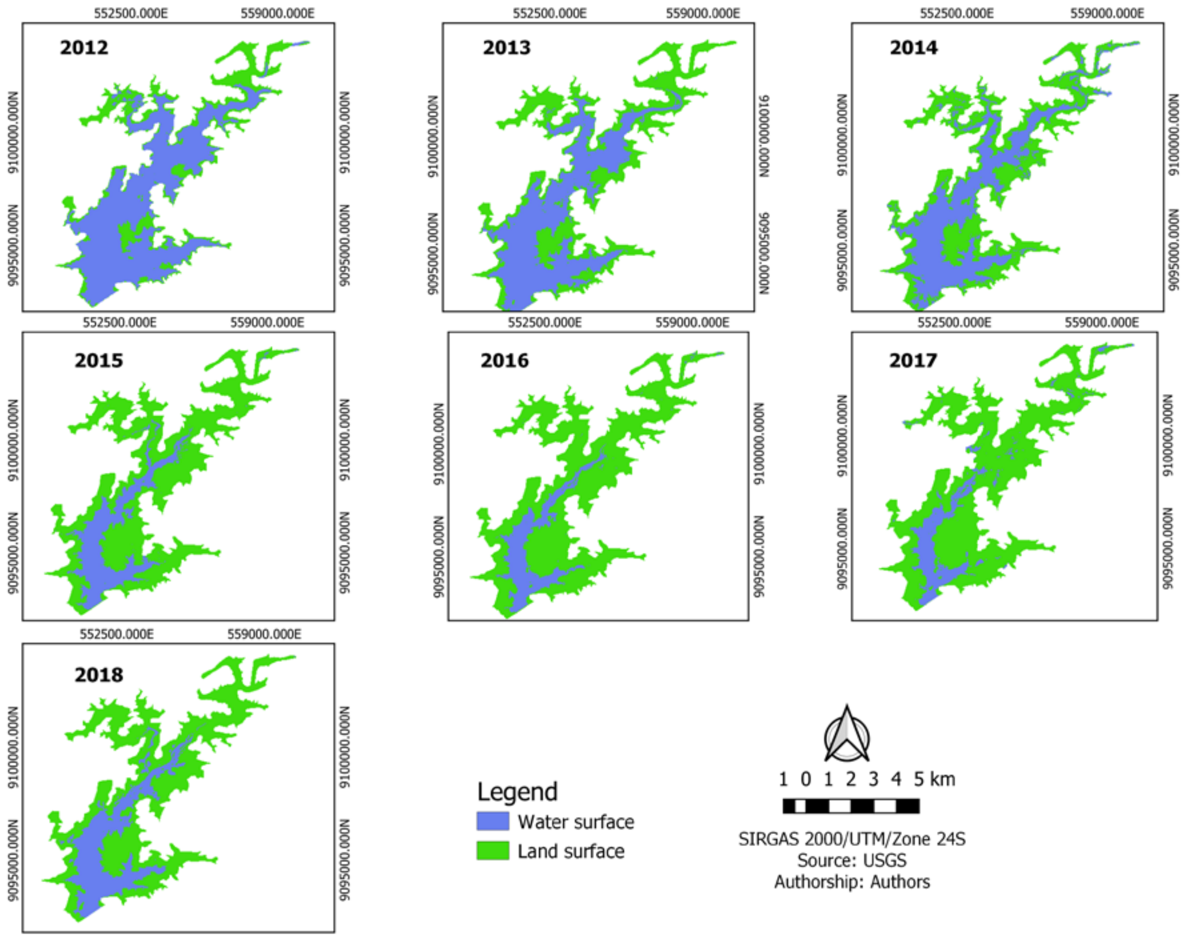

Figure 6 Reservoir maps using the SVM algorithm, from 2012 to 2018.

Table 1 Accuracy and Kappa values expressed by SVM ratings.

Observation year	Global accuracy	Kappa
2012	0.9988	0.9761
2013	0.9965	0.9193
2014	0.9911	0.8190
2015	0.9836	0.6054
2016	0.9846	0.6450
2017	0.9784	0.7534
2018	0.9895	0.7641

Table 2 Quantification of the reservoir area (hectares) throughout the study period.

Year	MapBiomas	NDWI	SVM	Difference (ha)		
				MapBiomas – NDWI	MapBiomas – SVM	SVM – NDWI
2012	2409.97	2107.44	2470.34	302.53	-60.37	362.9
2013	1969.16	1661.49	1834.00	307.67	135.16	172.51
2014	1508.97	1188.27	1600.42	320.7	-91.45	412.15
2015	916.98	676.98	823.78	240.00	93.20	146.80
2016	669.76	461.61	585.94	208.15	83.82	124.33
2017	567.26	284.58	538.24	282.68	29.02	253.66
2018	881.48	642.96	997.18	238.52	-115.70	354.22

Figure 7 presents the water dynamics in the Serrinha II reservoir from 2012 to 2018, highlighting the significant water coverage losses in the area. The class "other uses" refers to the areas that remained in the period from 2012 to 2018 with their respective classes. In red, the areas covered by water in 2012 became land or vegetation coverage in 2018.

The three reservoir identification methods generated similar results in the evaluation of water coverage temporal dynamics. Data from MapBiomas accounted for a water surface reduction of 1528.49 ha from 2012 to 2018. The NDWI index showed a water area loss of 1464.48 ha, while the SVM algorithm identified a reduction of 1473.16 ha.

4 Discussion

The reduction in water coverage alters land use and land occupation with a predominance of arboreal and shrubby vegetation. França et al. (2020) identified the correlation between land use and land cover with rainfall in the Pajeú River basin. The authors stated that the vegetation of this biome does not rely exclusively on the hydric reload from the same year but rather from previous years, showing susceptibility to fragmentation because of the variability in climatic conditions and the botanical characteristics of the predominant vegetation of the Caatinga.

The Mapbiomas and SVM methods showed similar results since they used automatic classification based on machine learning and integrated with the Google Earth Engine and annual image database from Landsat (Souza Jr et al. 2020; Neves et al. 2020).

The SVM classification enabled the identification of reservoir dynamics throughout the years, demonstrated by a slight increase in the area classified as "water" in 2018, which supports the data collected from the rainfall station. The results corroborate to Petropoulos, Arvanitis and Sigrimis (2012), who concluded that the precision of the SVM classification could be ascribed to the ability to identify an ideal hyperplane for the separation of classes, which allows a slight error of generalization, thus generating optimal separation of classes.

Generally, the results obtained by AI techniques require adjusting the algorithm, which involves significant effort, and less complex techniques such as the elaboration of vegetation indices can be adopted. The NDWI index, in turn, was shown to encompass a large part of the field variability when used to observe reservoirs.

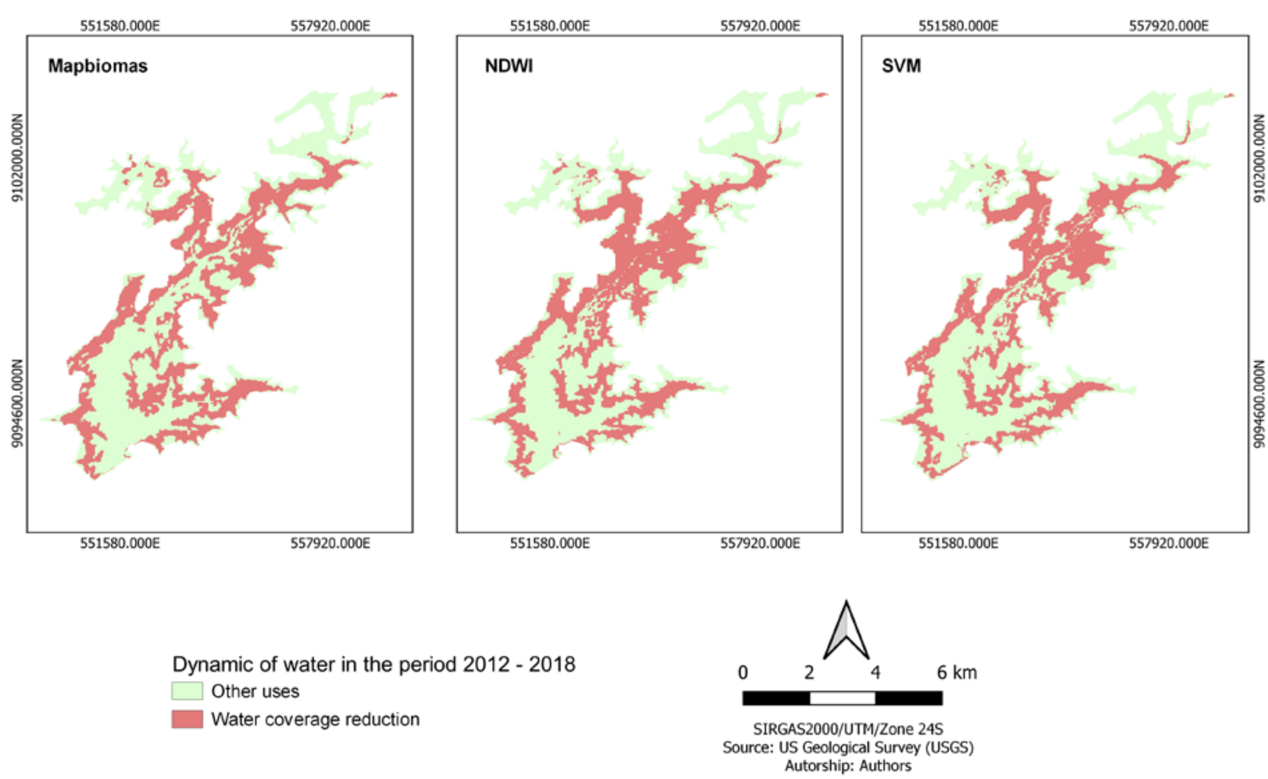

Figure 7 Dynamics of water in the period from 2012 to 2018: "other uses" refers to the areas that presented no coverage modification (green), and "water coverage reduction" refers to areas that modified from water to other uses coverage (red).

Despite the differences when compared to the MapBiomas and SVM classification data, the NDWI is sensitive to the moisture content of terrestrial targets, making it relevant for monitoring water reservoirs. So, the present study reinforces the importance of this variable in water resources monitoring, especially in regions characterized by long periods of drought. Andrade et al. (2018) assessed remote sensing techniques using NDVI and NDWI in the semi-arid regions of Exu and Moreilândia and found that the NDWI values were directly proportional to those of NDVI.

In this sense, geotechnologies are a practical alternative for monitoring reservoirs in the semi-arid region, enabling more efficient and faster water management. As pointed out by Pilz et al. (2019), remote sensing products can improve the exploitation of the capabilities of models, especially process-based hydrological models. The classification methods allowed for observing water dynamics, which may provide more in-depth information and understanding of behavior patterns (Condeça, Nascimento & Barreiras 2022).

The reduction in stored volume from 2012 to 2018 highlights how the drought is a critical factor in the storage capacity of reservoirs, especially in semi-arid areas. Drought is a complex meteorological phenomenon influenced by different factors such as precipitation, soil characteristics, humidity, soil, and air temperature, wind speed, land use, and land cover (Dobri et al. 2021; Benzougagh et al. 2022). Under these conditions, water resources become extremely important for maintaining economic and social activities, but more robust studies of precipitation, evaporation, infiltration and other hydrological elements to local reservoir dynamics are needed.

5 Conclusions

The hydric mapping of the semi-arid regions obtained using NDWI was similar to that using SVM and Mapbiomas, owing to the ease of use and rapid data acquisition. Thus, the NDWI is a viable alternative for identifying changes in water bodies.

Drought in semi-arid regions areas is critical for decreasing water availability in reservoirs. From 2012 to 2018, the reduction of reservoir water was 63.42, 69.49, and 67.69%, considering the Mapbiomas, NDWI, and SVM methods.

Therefore, the results for land use and cover obtained by classifiers are reliable for understanding the dynamics of water bodies in semi-arid regions. However, it is essential to develop field validation of the classifications in further studies. In addition, it is interesting that future studies analyze surface water availability and its relationship with precipitation, evaporation, and other hydrological elements.

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Wilson dos Anjos Carvalho: conceptualization; methodology; validation; writing-original draft; visualization. **Alan Cézar Bezerra:** conceptualization; methodology; formal analysis; validation; writing-original draft; writing – review and editing; visualization. **Elisiane Alba:** methodology; validation; writing – review and editing. **Luciana Sandra Bastos Souza:** methodology; formal analysis; writing – review and editing. **Anderson Santos da Silva:** formal analysis; visualization. **Geber Barbosa de Albuquerque Moura:** supervision.

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