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Spatio-temporal variation of aquatic macrophyte cover in a reservoir using Landsat images and Google Earth Engine

Variação espaço-temporal da cobertura de macrófitas aquáticas em reservatório usando imagens Landsat e Google Earth Engine

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ABSTRACT

The presence of large amounts of aquatic macrophytes in reservoirs can trigger several impacts on the local ecosystem and conventional methodologies used for their monitoring only returns information from the present moment. With that in mind, this study aimed to map spatio-temporal variation of macrophyte cover using Landsat 5, 7 and 8 images between 1984-2021 at Jupiá reservoir, in south east of Brazil, besides determining curves and maps of macrophyte cover permanence. The identification of these organisms in the images, and their distinction from other vegetations, was made through spectral indices (NDVI, GNDVI and GSAVI) and the determination of the characteristic range of each of these classes, which was given by probability distributions. Interannual variations were observed in the spatial arrangement of macrophytes and the area's growth trend, possibly being caused by the implantation of an upstream reservoir. Although the number of images without interference was a limitation, the construction of a historical series of macrophytes occupation and the determination of permanence curves and maps proved to be satisfactory and could help on the decision-making processes for the management of these organisms.

Keywords: Remote sensing; Aquatic macrophytes; Jupiá Reservoir; Growth trend; Seasonality; Flows.

RESUMO

A presença de grandes quantidades de macrófitas aquáticas em reservatórios pode desencadear diversos impactos no ecossistema local e o uso de metodologias convencionais para seu monitoramento retorna apenas informações do momento presente. Com isso em vista, este estudo teve como objetivo mapear a variação espaço-temporal da cobertura de macrófitas utilizando imagens Landsat 5, 7 e 8 para o período de 1984-2021 no reservatório Jupiá, Brasil, além de determinar curvas e mapas de permanência da cobertura de macrófitas. A identificação desses organismos nas imagens, e sua distinção de outras espécies vegetais, foi feita através de índices espectrais (NDVI, GNDVI e GSAVI) e da determinação do intervalo característico de cada uma dessas classes, a qual se deu por distribuições de probabilidade. Foram observadas variações interanuais na disposição espacial das macrófitas e tendência de crescimento da área, sendo este último possivelmente causado pela implantação de um reservatório a montante. Apesar da quantidade de imagens sem interferências ter sido uma limitação, a construção de uma série histórica de ocupação de macrófitas e a determinação de curvas e mapas de permanência mostraram-se satisfatórias e poderão auxiliar na tomada de decisões de manejo desses organismos.

Palavras chave: Sensoriamento remoto; Macrófitas aquáticas; Reservatório Jupiá; Tendência de crescimento; Sazonalidade; Vazões.

INTRODUCTION

Hydraulic construction implementation for energy generation, such as the damming of rivers to form reservoirs, causes changes in the region's ecosystem and in the river's hydrodynamics. The increased propensity to accumulate nutrients in the reservoir region is an imbalance that, combined with the characteristics of tropical and subtropical climates, such as high temperatures and high solar incidence, can trigger the proliferation of aquatic macrophytes. As occurred at the Engenheiro Souza Dias Hydropower Plant - HPP (located on the border between the states of São Paulo and Mato Grosso do Sul, Brazil), when presented in large quantities, causing losses (about R$ 3.8 million in maintenance) and interruptions in energy generation through the obstruction of the water intake conduits (making a total of 10 generating units unavailable for about 5 months) (China Three Gorges Brasil Energia Ltda, 2019). These organisms must be monitored as a result of negatively impact to the environment, reducing the diversity of floristic species, causing fauna's mortality, besides damage and interruptions in energy generation (Esteves, 1998).

Conventional monitoring methodologies used to quantify aquatic macrophytes can be costly and time-consuming (Luo et al., 2016; Zhao et al., 2012), given the extensive area of the reservoirs. Moreover, the sample universe obtained by conventional methodologies only includes present information. In this way, the use of remote sensing as a complementary tool to on-site monitoring has proved to be an interesting alternative to this limitation, both due to the amount and availability of data, as well as the possibility of obtaining retroactive information and, with that, observe the historical evolution of macrophyte growth in reservoirs (Bai et al., 2020; Coladello et al., 2020; Luo et al., 2016). In addition, even using images taken from short periods, it is possible to verify the presence or absence of specific behaviors between different periods of the year (Minhoni et al., 2017; Tena et al., 2017) or even verify the influence of anthropic activities or climate change in the growth of macrophytes (Bezerra Junior, 2021; Lima et al., 2018; Minhoni et al., 2018).

Water quality analysis, and especially macrophyte monitoring has been done by point measurements up to know, without being possible to quantify covered areas, neither temporal variation and transport of macrophytes. Although the monitoring of these organisms is a current concern (given the damage caused to energy generation, for example) there is currently no database for monitoring macrophytes in water bodies, nor is their monitoring mandatory. This results in the lack of historical information on the evolution of macrophytes in reservoirs. This scientific gap has been addressed by using remote sensing techniques, capable to map regions covered with macrophytes, and track their changes over time. Accordingly, it is considered that knowing the spatial and temporal evolution of macrophytes in reservoirs is relevant in decision-making regarding reservoirs operation and in the management actions of these organisms. In this context, the aim was to verify if there was a spatio-temporal variation of aquatic macrophytes in the Jupiá reservoir (Engenheiro Souza Dias HPP), between 1984-2021, through the determination of the historical series of the macrophytes area by remote sensing. This study also aimed to determine macrophyte permanence curves and maps to be used as a comparing basis of new macrophyte mapping information from the alert system in operation at HPP. Equally important, it was also analyzed if climatic characteristics of the region (precipitation and temperature) reproduced any interannual seasonal behavior in the macrophytes cover, and if the land use change and the operations of upstream hydropower plants contributed to the increase in the area of macrophytes over the years.

MATERIAL AND METHODS

The study area– the reservoir of Engenheiro Souza Dias HPP, also known as Jupiá – is target of a research project in progress (Research and development project - P&D ANEEL 10381- 0819/2019), by Lactec and the concessionaire that manages and operates the Engenheiro Souza Dias HPP, CTG Brasil, related to the development of an Emergencies Action Plan for Macrophytes. It is noteworthy that the activities developed in this paper are included in this P&D ANEEL project.

This study follows on from another P&D project (nº 10381-0317 - Monitoring the development and displacement of aquatic macrophyte banks in reservoirs using geotechnologies and remote sensing techniques). Together, of the numerous products developed in these two studies, we can mention the diagnosis of water quality and a floristic survey, through onside collections (Instituto de Tecnologia para o Desenvolvimento, 2019a), a Macrophyte Monitoring System through remote sensing, which was implemented to an alert system (Instituto de Tecnologia para o Desenvolvimento, 2019b) currently used by the concessionaire in the HPP operation, in addition to the determination of critical locations for monitoring through the spatial analysis of macrophyte permanence (Instituto de Tecnologia para o Desenvolvimento, 2020).

Study area description

Formed in 1968 by the damming of the Paraná, Tietê and Sucuriú Rivers (Figure 1), the Jupiá reservoir has a storage volume of 904 hm^3, spread over 330 km^2 with 482 km perimeter and it is located between São Paulo and Mato Grosso do Sul states (Mustafa et al., 2010). Its main use is power generation at the Engenheiro Souza Dias HPP, which operates as a run-of-the-River reservoir with constant power generation, with an average annual water residence time of 6.39 days (Companhia Energética de São Paulo, 2009). The water level near the dam (altitude of 229 m) remains on average at 279.6 m, with minimum depletions of $\pm$ 0.50 m, and as a consequence, there is no formation of intermittent ponds. Besides, a significant part of the reservoir has depths of around 3.50 m and reaches up to 45 m in a small branch of the Paraná River.

The climate in the region is tropical savannah (Aw), according to the Köppen-Geiger classification. The region has an average annual rainfall of around 1200 mm, with rainy Summers and dry Winters with an average annual temperature of 24°C.

Jupiá's water quality is characterized by high water transparency, in which in some regions it is possible to see the Riverbed even at depths of 3 to 5 m (total Secchi Disk). Regarding the amount of

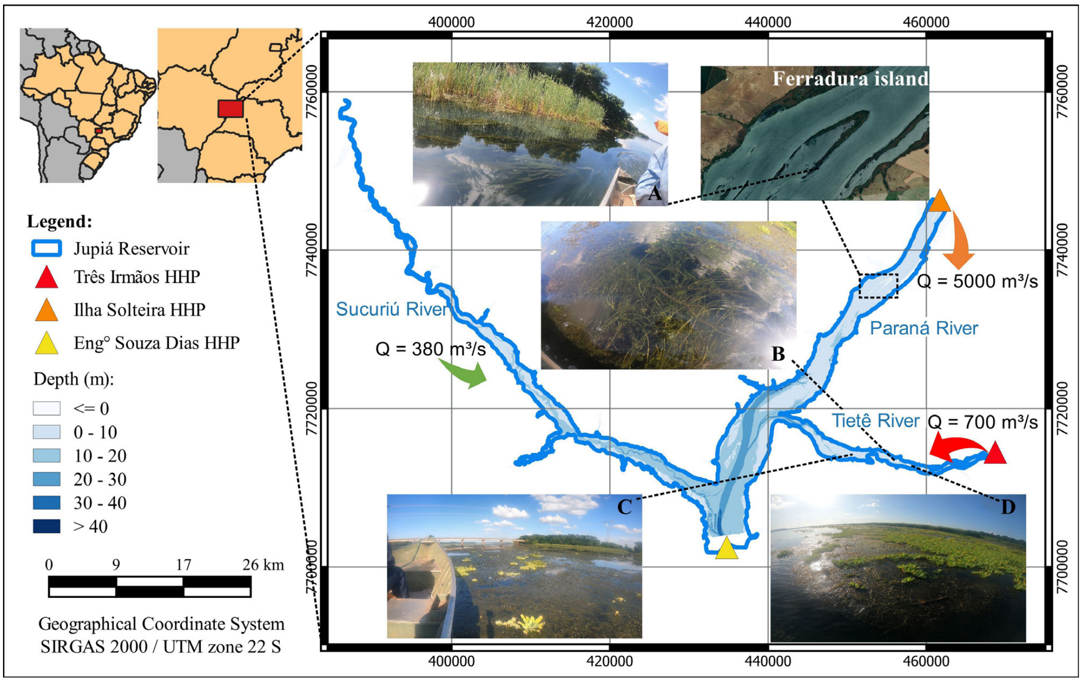

Figure 1. Location, some of the macrophyte species found and the depth of the Jupiá reservoir. (A): Field research photographic records (04/05/2022) of *Egeria densa* and *Typha domingensis* near Ferradura Island, in the Paraná River; (B): Field research photographic records (04/06/2022) of *Egeria densa* and *Egeria najas* upstream of the Tietê River Bridge, on the Tietê River; (C): Field research photographic records (04/06/2022) of *Egeria densa, Egeria najas* and *Pistia stratiotes* downstream of the Tietê River bridge, on the Tietê River and; (D): Field research photographic records (04/06/2022) of *Egeria densa*, *Egeria najas* and *Pistia stratiotes* upstream of the Tietê River Bridge, on the Tietê River.

nutrients available, it was observed that phosphorus was the limiting element in most of the monitored period (2018-2019). Concentrations above 0.050 mg/L (class 2 freshwater limit by CONAMA resolution nº 357/2005) were found in 4 of the 6 campaigns carried out, with the highest value of 1.56 mg/L on Ferradura Island in December/2018. As for total nitrogen concentrations, in no sample the legislated limits for fresh waters of Classes 1 and 2 (2.18 mg/L) were exceeded (Instituto de Tecnologia para o Desenvolvimento, 2019a).

Due to these characteristics, the Jupiá reservoir has an abundant occupation of aquatic macrophytes that can detach and move to the dam following the flow. This amount is so expressive that in 2017, this phenomenon was responsible for stop the energy generation due to the clogging of the water intake structures (China Three Gorges Brasil Energia Ltda, 2019).

Instituto de Tecnologia para o Desenvolvimento (2019a) carried out a floristic survey in which the species of aquatic macrophytes with the highest occurrence were identified (*Egeria densa*, *Egeria najas* and *Typha domingensis* (Figure 1) and the characteristic of the place where they were found. Free submerged species were found on the banks, and submerged ones rooted in the central area of the reservoir. The floating and rooted ones were found in more protected areas, such as shores and ponds.

Macrophytes identification in Landsat images

The macrophyte identification procedure in the satellite images consisted of 14 steps (Figure 2) and the use of images from the USGS Landsat 5, 7 and 8 collections (Collection 2, Level 2), orbit 223 (WRS PATH), which have spectral resolution of 30 m and with previous atmospheric surface reflectance corrections (BoA) by the TM, ETM+ and OLI/TIRS sensors, respectively. Since the aim is the historical knowledge of the region, preference was given to these collections over other options due to the interval of data availability being over 30 years. These images were processed using the Google Earth Engine – GEE (Google Earth Engine, 2022) due to the wide catalog of satellite images and, mainly, because the processing is carried out in the Google cloud, which enables the use of many images, since downloading them is not necessary. It should also be noted that the R-4.1.3 and Python 3.9.7 languages were used for statistical analysis and data visualization.

Initially, images from March/2016 to June/2020 that had cloud cover up to 2.5% were selected for the insertion of sample points of three classes: water, macrophyte and other vegetation. This procedure was carried out with the objective of verifying the limit of the separation between the classes in the spectral indices. Cloud cover was limited in order to reduce data interference. This value was assumed after realizing that the number of images with cloud cover up to 2.5% was already considerable and that adding images with higher cloud cover could compromise the data quality. The period used coincides with data compiled in maps of permanence (in regions with probability of occurrence of water, macrophytes and other vegetation) reported in (Instituto de Tecnologia para o Desenvolvimento, 2020).

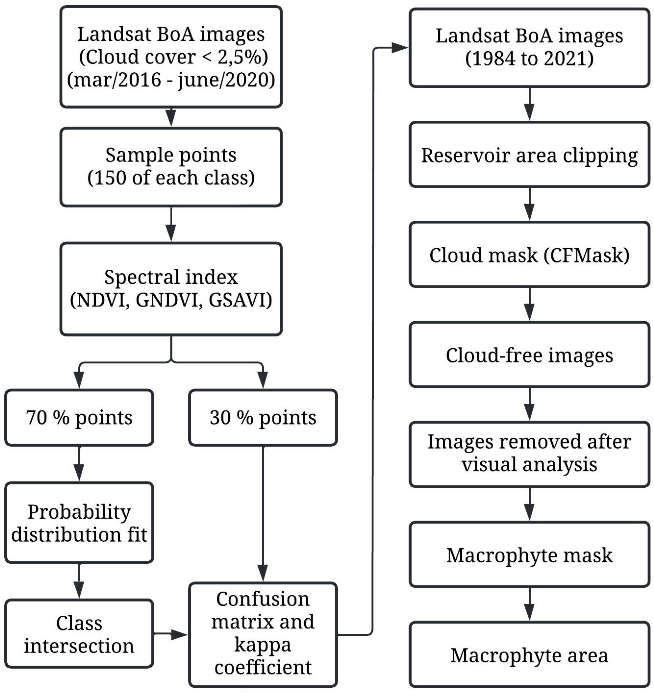

Figure 2. Aquatic macrophytes classification process flowchart in Landsat 5, 7 and 8 images.

Thus, of the 65 images available, after a quick visual analysis, 32 were discarded due to the failure of the ETM+ sensor and 6 due to cloud interference in the reservoir region. In all, 27 images were considered suitable for use, and in each one of them were inserted: 150 water points, 150 of macrophytes and 150 of other vegetation; based, in addition to the analysis of macrophyte permanence (Instituto de Tecnologia para o Desenvolvimento, 2020), field photographic records (Figure 3). These known sampling points were entered to be used as in a supervised classification in the GEE, as described below. As the study area is limited to the reservoir, in addition to the differentiation between water and macrophytes, it was considered convenient to distinguish between macrophytes and other vegetation, the latter presented and fixed on islands inside the reservoir (the visualization can be found in the Supplementary Material, Figure SP3).

To verify the boundaries between classes, for each class, from 4050 points (150 points in 27 images), 70% were randomly selected to observe the frequency of the spectral indices NDVI, GNDVI and GSAVI and in the bands that compose them: Red (0.63 to 0.69μm), Green (0.52 to 0.60μm) and NIR (0.77 to 0.90μm). With these data, for each index, 16 probability distributions were adjusted and it was verified which probability distribution would best suit the sample of each class, considering the result of the Anderson-Darling (AD) adherence test (Naghettini & Pinto, 2007), in order to verify the limit values that characterize the class of macrophytes. The best index-interval was defined through a validation, in which, with the remaining 30% of points, the confusion matrices and the Cohen's kappa coefficient (Landis & Koch, 1977) of each model were calculated.

After defining the best index and range for macrophyte identification, all images between the years 1984 and 2021 (597 images) were clipped, in order to encompass only the representative polygon of the reservoir area to the height 280 m (operational quota), and a cloud mask was applied to select only cloud-free images. Images that met this condition (179 images) underwent a quick visual analysis and it was necessary to discard the images which presented interference in the reading due to the sunlight (5 images), by the attenuation of the color (30 images) and images that did not contemplate the entire reservoir (2 images) (the visualization can be found in the Supplementary Material, Figure SP2). Next, a macrophyte mask was applied to the remaining images (142 images), so that the macrophyte area was calculated by counting pixels.

Curves and maps of macrophyte area permanence

After calculating the area of macrophytes in each image, a permanence curve was calculated, in which the area values were ordered in descending order to calculate the frequency with which this area was equaled or exceeded, using the Kimbal's method (Pinto et al., 1976). This method differs in calculating the frequency, in which it is not possible to reach the value of 100%.

Additionally, by mapping the spatial distribution of macrophytes in each image, the permanence of macrophytes in each pixel was calculated. The procedure was performed using the 'raster calculator' tool of QGIS 3.16.16-Hannover software, through the sum of all macrophyte masks and frequency calculation was also done by the Kimbal method.

In both analyses, in addition to observing the complete series, the data were also grouped seasonally, to verify if there were interannual variations, and also by decades to evaluate.

Environmental variables effects on macrophyte growth

One of the indirect ways of verifying changes in nutrient availability is through changes in land use, since the increase in human activities, such as urbanization and agriculture, is a factor that can cause eutrophication of water bodies. To investigate this phenomenon, the watershed of the Jupiá reservoir was delimited (considering the dam as an outlet), and the incremental areas of each contribution from the reservoir were also calculated: Sucuriú River (considering the beginning of the reservoir as an outlet) and the reservoirs of Ilha Solteira and Três Irmãos (both considering the dam as an outlet for the basin). In these areas, annual land cover data between the years 1985-2020, from the MapBiomas (Projeto MapBiomas, 2022) – a collaborative project of NGOs, universities and startups that carries out the annual mapping of land use and coverage in Brazil – also through the GEE platform, were used to verify variations in land cover in this period, considering the initial year of 1985 as a base. As there is no variation in Jupiá water level, to verify the influence of the reservoir hydrodynamics on the macrophytes growth, the average monthly outflows of the upstream plants of Jupiá (Ilha Solteira HPP and Três Irmãos HPP) were analyzed, while, to ascertain the influence of climatological conditions, Pearson's correlation between the macrophyte area

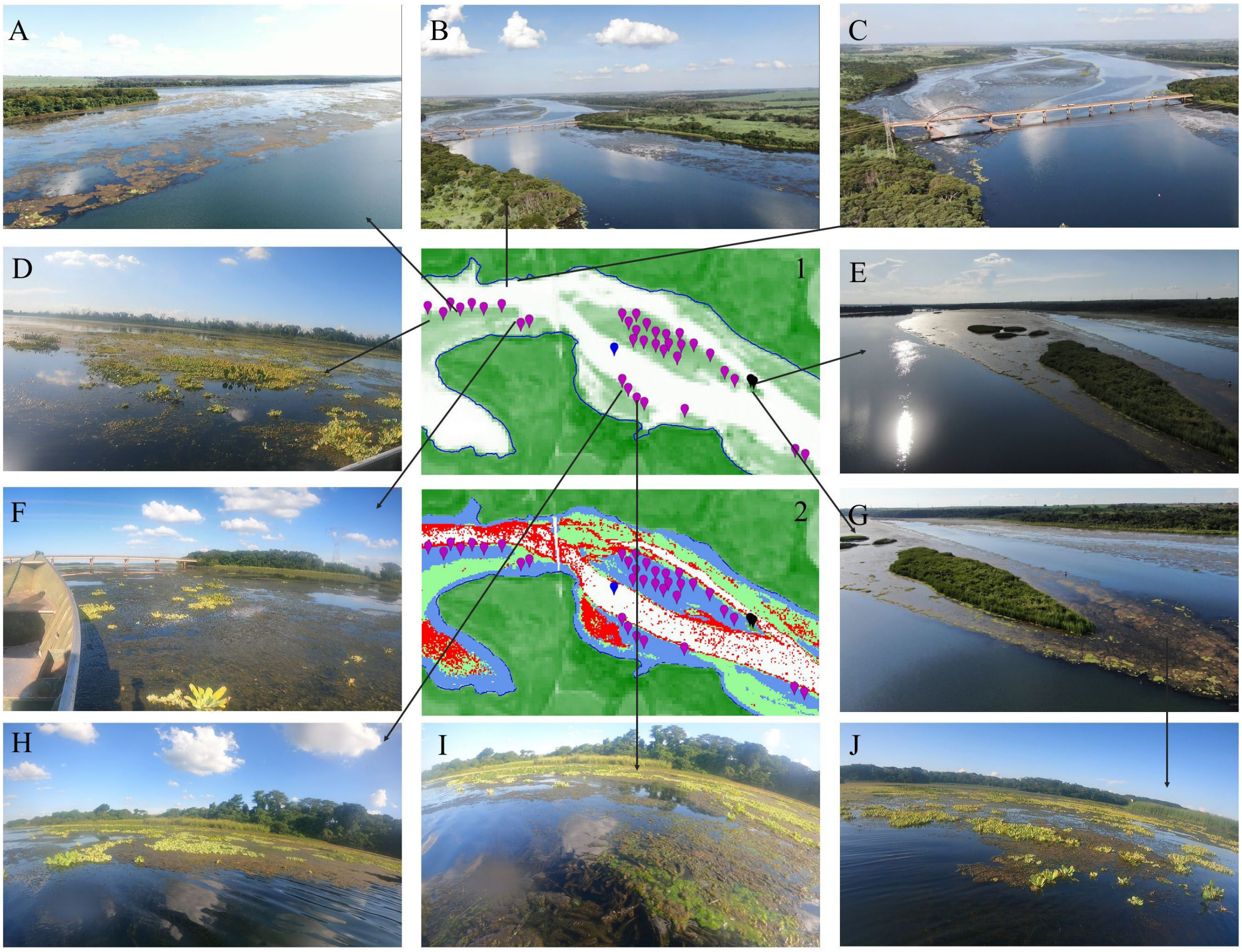

Figure 3. Field research photographic records and details of water, aquatic macrophytes and other vegetations sample points: (1): GSAVI Landsat image (05/03/2017) of the Tietê River region with the sampling points (black - other vegetations; purple – macrophytes; blue – water); (2): GSAVI Landsat image (05/03/2017 of the Tietê River region with the macrophyte permanence areas (blue – high permanence; green – intermediate permanence; red – low permanence; white - no permanence) (Instituto de Tecnologia para o Desenvolvimento, 2020) and; (A, B, C, D, E, F, G, H, I, J): Field research photographic records (04/06/2022).

and the monthly mean air temperature and monthly precipitation were analyzed, from 2014 to 2021.

RESULTS AND DISCUSSION

Macrophytes identification in Landsat images

To verify the boundary between the classes (water, macrophyte and vegetation), the 70% of sampling points frequency of the NDVI, GNDVI and GSAVI spectral indices were analyzed, in addition to the bands that compose them: Red, Green and NIR (Figure 4).

In the histograms, it can be seen there was a massive overlap from three classes for Green, while for Red, the overlap was not so great between the macrophyte and vegetation classes, although it still exists. For the NIR band, the overlap was smaller when compared to the visible bands (Green and Red).

The values recorded in the water class correspond to the spectral behavior expected by this class: great absorption of NIR radiation and low reflectance in the visible bands (Novo, 1998); which implies negative and close to zero values of the analyzed indices (Gitelson et al., 1996; Huete, 1988; Rouse et al., 1973).

The macrophytes and other vegetation values followed the general behavior of vegetation: they reflect a lot of NIR radiation and little of visible radiation; which implies positive values for the analyzed indices (Gitelson et al., 1996; Huete, 1988; Rouse et al., 1973). The difference between these classes may be in the color of each species (Red) as well as in the water interference on macrophytes (Novo, 1998).

For the three spectral indices, it was possible to observe an overlap between the macrophyte and other vegetations classes and a distinct separation between the water and macrophyte classes, which is the reason by only the intersection between the macrophyte classes and other vegetations was verified. With these data, for each index, 16 probability distributions were adjusted and the value of the Anderson-Darling (AD) adherence test (Naghettini & Pinto, 2007) was evaluated. For all indices, of the curves tested with data from other vegetations, none showed an acceptable p-value (p-values < 0.05), while for macrophytes data, only the

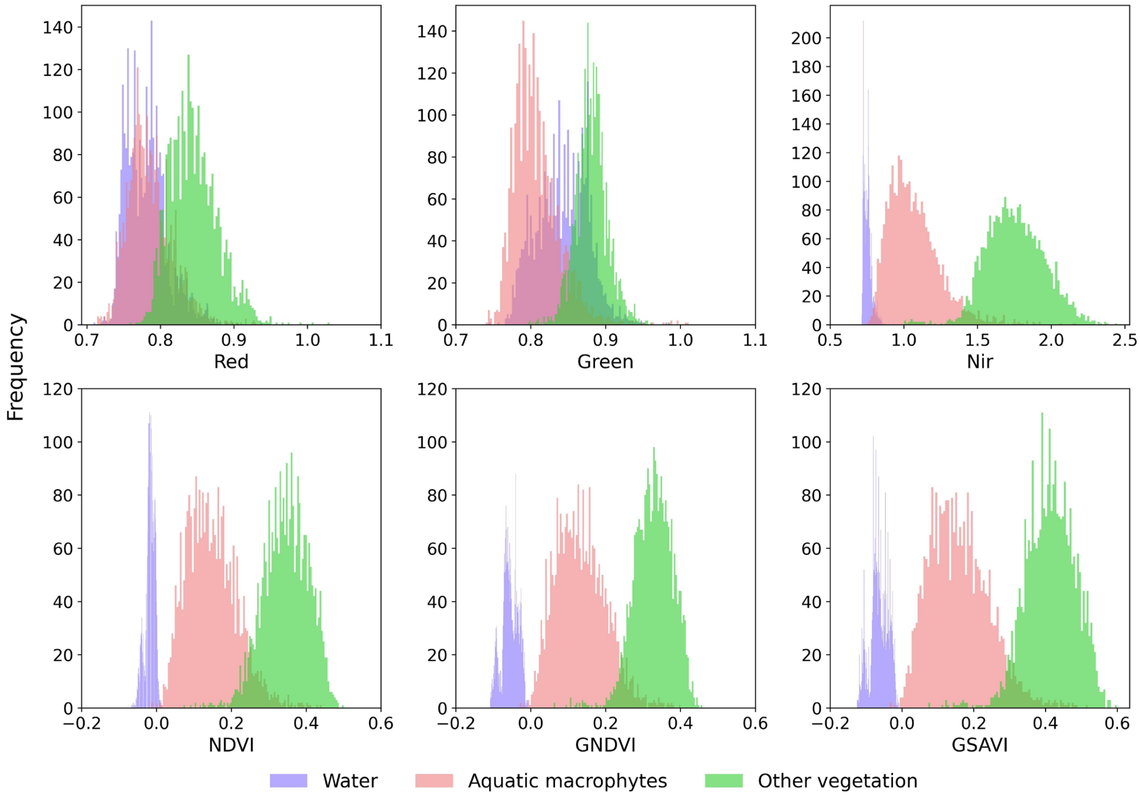

Figure 4. Frequency diagrams of Red, Green and NIR bands, and NDVI, GNDVI and GSAVI spectral indices considering 70% of the water, macrophyte and other vegetation data.

Table 1. Aquatic macrophyte classification confusion matrices and model accuracy: W[1] = Water; A.M.[2] = Aquatic Macrophyte and; O.V.[3] = Others Vegetation.

Index		**NDVI (0.045 – 0.249)**			**GNDVI (0.028 – 0.239)**			**GSAVI (0.024 – 0.294)**		
Actual class		**W[1]**	**A.M.[2]**	**O.V.[3]**	**W**	**A.M.**	**O.V.**	**W**	**A.M.**	**O.V.**
Predicted Class	W	1,252	0	0	1,252	0	0	1,252	0	0
	A.M.	0	1,169	71	0	1,173	41	0	1,176	37
	O.V.	0	71	1,181	0	67	1,211	0	64	1,215
Kappa			**0.962**			**0.971**			**0.973**	

3-parameter Weibull distribution met the test (p -value = 0.073). Anyway, it was found that in the region of intersection between the classes, both macrophytes and other vegetation data can be approximated by a normal distribution (the visualization can be found in the Supplementary Material, Figure SP3).

Thus, for each index, the upper limit of the macrophyte class was determined from the value where the macrophyte classes and other vegetations PDF curves (probability density function) coincided. The macrophyte class lower limit was given by the PDF curve, in order to encompass 90% of the data, based on the value of the upper limit.

With the limits of each index determined, to find out which index-interval set presented the best behavior, the 30% remaining points of each class were used to calculate the confusion matrix and the Kappa coefficient.

It was observed the three index-interval sets presented high values for the Kappa coefficient (Table 1), being the use of any of them very satisfactory for aquatic macrophytes identification in Landsat images (Landis & Koch, 1977).

Therefore, the GSAVI index-interval set (0.024 to 0.294) was adopted, because its result was superior to the others. For the water classification, all values below 0.024 were considered, while for other vegetation, all values above 0.294. For instance, two images were selected - being: one before (Figure 5A) and another after the May/2017 event (Figure 5B) – in which it is possible to notice the macrophytes cover change in the region of the Paraná River, and of even more substantially on the Tietê River.

Macrophyte area historical series

Of all 597 Landsat images available between 1984-2021, 418 images were discarded because of cloud interference, after applying a cloud mask to each one. Processing a large number of images was

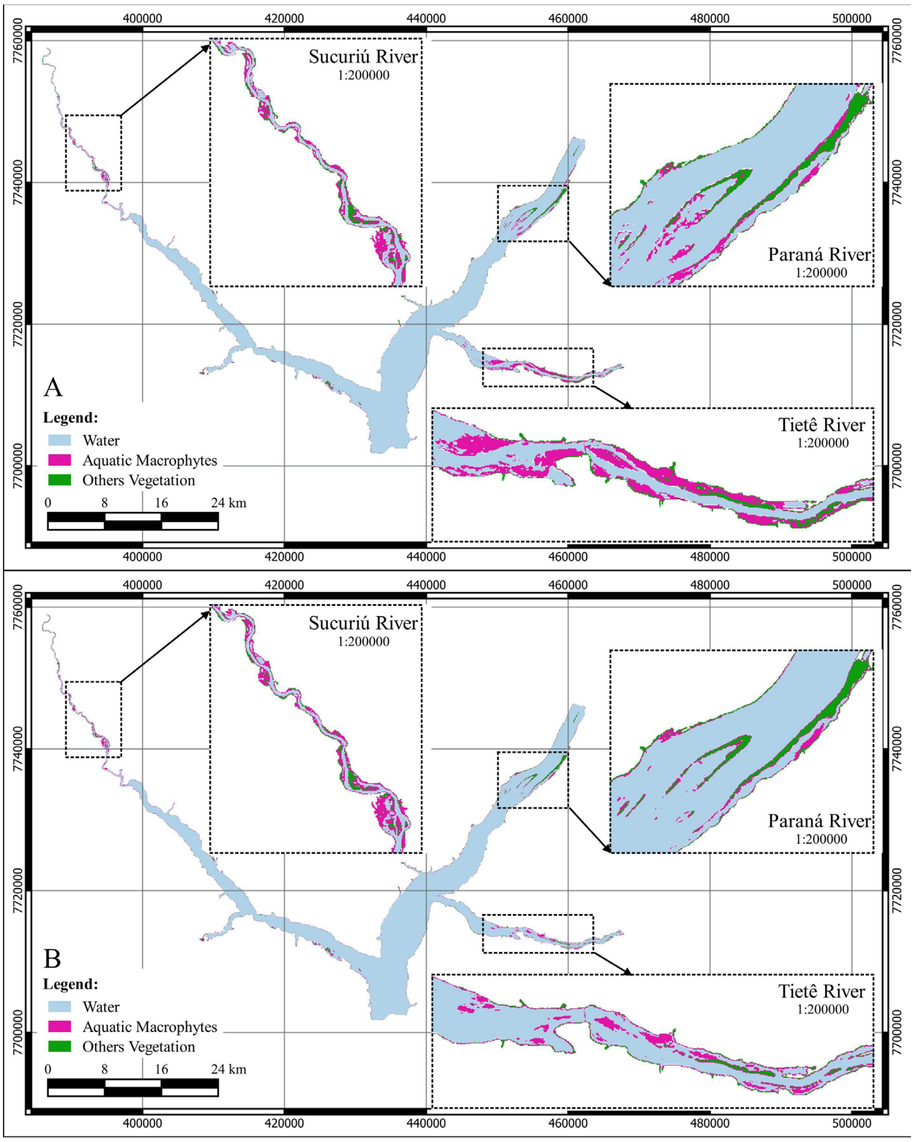

Figure 5. Aquatic macrophytes identification in the Landsat 8 image for A) May/2017 and B) July/2017.

feasible due to the use of the GEE tool, which returned the result in a few minutes. Of the remaining 179 images, only 142 images were considered suitable for use, due to sunlight interference and presenting a more attenuated color. These images are heterogeneously distributed over time (Table 2), since in 2003, 2011, 2012 and 2013 there were no appropriate images, also there are different amounts of images between years, and in a year, between seasons.

Macrophytes identification in these images was performed by applying the macrophyte mask using the GSAVI index (0.024-0.294), while the area was determined by counting pixels. It was possible to notice a growth trend (stationarity hypothesis rejected) with the advancement of time (Figure 6A), in which, by adjusting a linear trend (R^2 = 0.41) the growth rate is 4.55 10^{-4} km^2/dia. The highest recorded area value was 26.57 km^2 on 12/21/2020 (8% of the reservoir area) while the smallest mapped area was on 03/14/1987 with 10.52 km^2 (3% of the reservoir area), accumulating a difference of more than 50%. The average area observed throughout the period was 16.83 km^2 (5% of the reservoir area). Other authors who used similar methodologies, and Landsat set images, also observed growth over the analyzed period (Coladello et al., 2020; Lima et al., 2018; Luo et al., 2016; Minhoni et al., 2017, 2018).

With the seasonality analyses throughout the historical series, it was possible to notice that there were decrease in areas in Winter and Spring, while in Autumn there was an increase (Figure 6A). Furthermore, until 1996, the largest areas occurred in Winter and/or Spring, however there was an inversion and since then these values have been recorded in Summer and/or Autumn. This is similar to what was described by Rosa et al. (2018) who found an increase in the area between March and April followed by a decrease between April and September in a branch of the Itaipu reservoir.

Likewise, from 2014 onwards, a greater number of elevated area is registered in Autumn, while smaller areas are registered in Winter, which could be a potential indicator that there is detachment and/or transport of macrophytes between these seasons.

Table 2. Quantity and temporal images distribution used to compose the macrophyte coverage time series between 1984-2021. (*): Landsat 5 TM, (#): Landsat 7 ETM+, (§): Landsat 8 OLI/TIRS.

Year	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	Total
Total	1	5	3	6	5	3	3	5	1	5	1	3	2	1	2	3	4	6	4	0	3	5	2	6	7	3	2	0	0	0	6	4	7	9	4	7	6	8	142
Jan											1*								1*																				2
Feb					1*																	1*												1§		1§			4
Mar		1*		2*			1*											1*							1*										1§	1§	1§		9
Apr						1*				1*			1*		1*		1*	2*	1*		1*			2*	1*	1#					1§	1§	2§	1§			1§	1§	20
May				1*	1*			2*		1*		1*				2*	1*	1*				1*			1#						1§			1§	1§		1§		16
June			1*	1*		1*	1*	1*				1*							2*		1*	1*		2*		1#	1#							1§		1§	1§	1§	18
Jul	1*	2*			1*		1*			2*				1*			1*	1*					1*		2#		1#				2§		1§	2§		2§		1§	22
Aug		1*	1*	1*								1*						1*				2*		1*	1#						1§	1§	1§	2§	1§		1§	2§	18
Sept					1*	1*																	1*	1*		1#					1§	2§	1§	1§	1§	1§		2§	14
Oct		1*	1*	1*				1*	1*				1*		1*																		1§			1§			9
Nov					1*			1*		1*											1*																		4
Dec																1*	1*								1#								1§				1§	1§	6

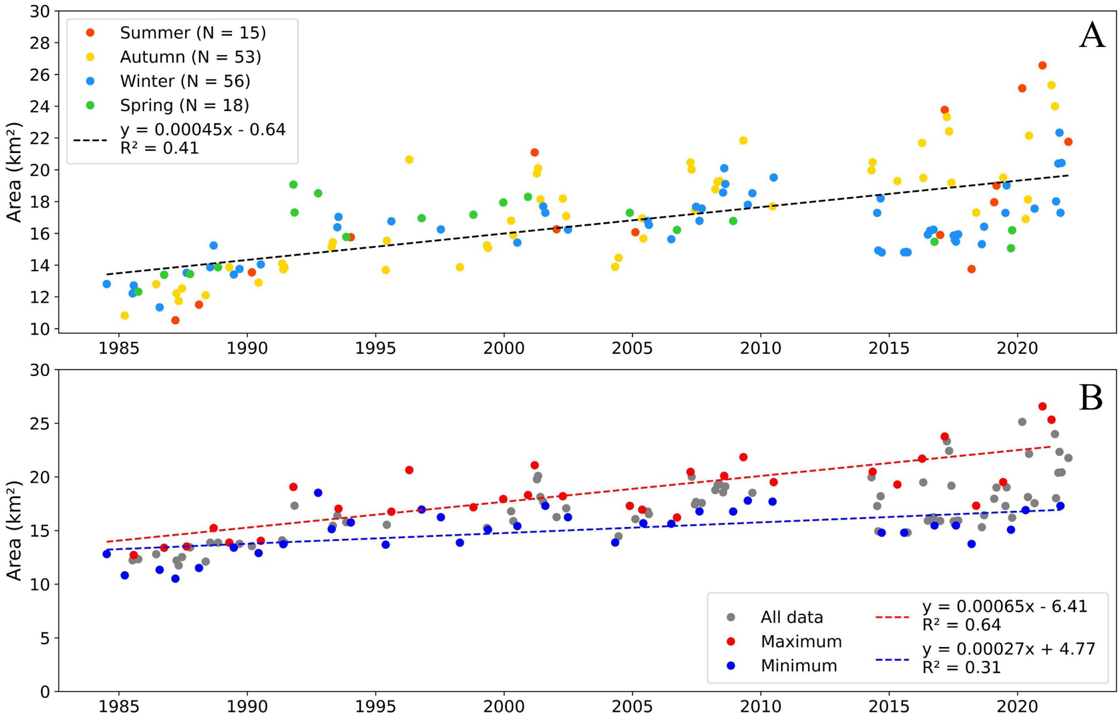

Figure 6. A) Macrophyte coverage area historical series for the 142 images selected using GSAVI index (0.024 - 0.294) and presented by season; B) Maximum and minimum areas of macrophytes and linear trend curve fit.

Furthermore, a growth trend over time it was also verified (stationarity hypothesis rejected) for the maximum and minimum values of each year. Curves were fitted for those data, which in, for the maximum annual area data, the fit was superior to the curve containing the complete series (Figure 6B).

Macrophyte area permanence curve

Macrophyte area permanence curves were calculated for the entire period analyzed and seasonally, separating all data into distinct curves for each of the decades and for each season.

Considering the complete series, the data could be satisfactorily fitted by a polynomial of third degree ($R^2 = 0.98$) (Figure 7A), although the maximum values were being underestimated. The curve showed a smooth behavior and similar to an S, which implies that intermediate values have little variation between them, and more accentuated variations at the ends.

Observing the behavior over the decades, it is possible to see the areas increased over the decades, especially when it comes to areas with the highest macrophytes cover, that is, frequencies < 50% and at maximum values (Figure 7A). For most of the time (frequencies > 50%), the 2000s presented values slightly higher than the 2010s, followed by the other decades in descending order. It is also noteworthy the curve of the 2010s was always higher than the historical series curve, corroborating the growth trend observed in the stationarity test and the results of others studies (Coladello et al., 2020; Lima et al., 2018; Luo et al., 2016; Minhoni et al., 2017, 2018).

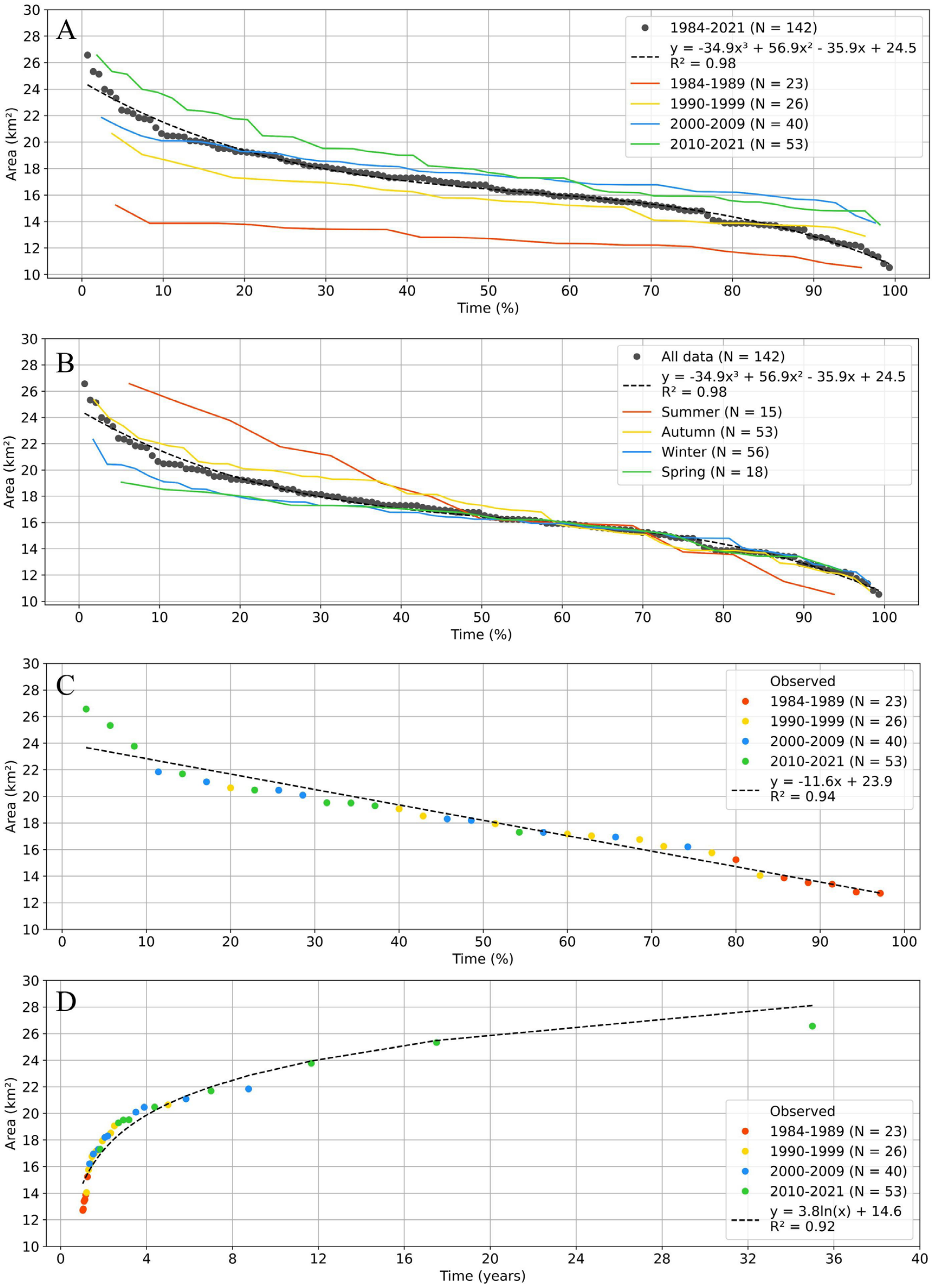

Figure 7. A) Macrophyte coverage area permanence curves for each decade (1984-1989, 1990-1999, 2000-2009 and 2010-2021), for the entire historical series (1984-2021) and its respective polynomial adjustment curve; B) Macrophyte coverage area permanence curves for each season (Summer, Autumn, Winter and Spring), for the entire historical series (1984-2021) and its respective polynomial adjustment curve; C) Permanence curve of maximum macrophyte areas and its respective linear adjustment; D) Return time curve of maximum macrophyte areas and its respective logarithmic fit.

In addition, the area variation was greater ($\sigma = 3.17$ km^2) in the 2010s, which is the broader curve than the others. The 1990s and 2000s had intermediate behavior and similar variations ($\sigma = 1.92$ km^2 and $\sigma = 1.79$ km^2, respectively), with the difference in the 2000s having values slightly higher than the previous one. Corroborating previous results, the 1980s were the decade that presented, besides the smallest variation ($\sigma = 1.12$ km^2), the smallest minimum, average and maximum values.

When it is analyzed seasonally, it can be seen again that the highest macrophyte areas were recorded in Summer and Autumn. In most of the analyzed time (84%), for all seasons, the occupancy area was greater than 14 km^2 (4% of the reservoir area), and in 50% of the time the macrophyte occupancy area remained between 16 and 18 km^2 (Figure 7B). This curve overlapping in the highest frequency region could may be a reflection of area variation between the seasons being smaller in the first half of the series (1985-2005) when compared to the final period (2005-2021).

The season that presented the greatest dispersion of values (σ = 4.89 km^2) was the Summer, which englobe the historical series of maximum and minimum values, with an amplitude of 16.05 km^2. Spring was the season with the lowest data amplitude (σ = 1.93 km^2), with the difference between its extreme values being 6.74 km^2. Luo et al. (2016) showed that the two groups of macrophytes analyzed by them had different behaviors between August and September (considering 5 years of measurements). The authors also point out that this difference may be related to many factors, such as biological growth characteristics of the species or vegetation harvesting, or even to classification errors. It is noteworthy that Summer and Spring were the seasons that presented about 3.5 times less images than Autumn and Winter, as the presence of clouds was the limiting factor, due to greater precipitation in this period. This limitation was already expected as a consequence the interference of clouds in the optical sensors of orbital satellites and was a common factor for the image's quantity used in several other studies (Coladello et al., 2020; Rosa et al., 2018).

Moreover, aiming at a trend analysis of extreme values, the permanence curve was also calculated for the maximum area recorded in each year (Figure 7C). The curve followed a decreasing linear behavior and was fitted to a 1st degree polynomial (R^2 = 0.94). Although the coefficient of determination is high, by the linear adjustment, the low frequency values (0% -10%, range that, for this analysis, is considered the most worrying) are underestimated when observed in the historical series. However, for the other frequencies, the adjustment was satisfactory. For most of the time (frequencies > 50%) the maximum area values ranged from 12 to 18 km^2, while for areas with higher macrophyte occupancy, that is, frequencies between 0 and 10%, there was a jump of 6 km^2.

As there is periodicity between the data in this series, the time of occurrence associated with the macrophytes permanence was also calculated (Figure 7D). The data follow a similar behavior to a logarithmic growth and were also adjusted (R^2 = 0.92). In this case, despite the coefficient of determination being high and well representative by the logarithmic adjustment for almost the entire series, the value associated with the longest time interval (35 years, a value that, for this analysis, is considered the most worrying) was overestimated.

Once more, in both analyses, it was found that the areas with the highest values correspond to the most recent decades, while the smaller areas correspond to the 1980s.

Macrophyte area permanence maps

Even before it is possible to calculate the area, the identification of macrophytes in the images through the application of the macrophyte mask using the GSAVI index (0.024-0.294) provides the spatial distribution in the reservoir, which made it possible to calculate the spatial shape permanence. For better visualization, the spatial distribution of macrophyte permanence was divided into three classes: low permanence (in blue), intermediate permanence (in green) and high permanence (in red) (Figure 8).

In the entire reservoir, three regions are worth mentioning. The first one is a stretch of the Tietê River, where, even with low permanence values, at some point almost all its extension was already occupied by macrophytes. Besides this low permanence, these values represent more recent areas of occupation, which indicates that macrophytes are developing in new areas of the reservoir. Another highlighted region is the initial stretch of the Paraná River, where we can observe the presence of macrophytes with greater permanence near the bank, while more central regions present lower permanence. As for the initial stretch of the Sucuriú River, it stands out for the high number of regions with a high permanence of macrophytes. For the other areas, in general, there is a predominance of macrophytes at the reservoir banks (Figure 8).

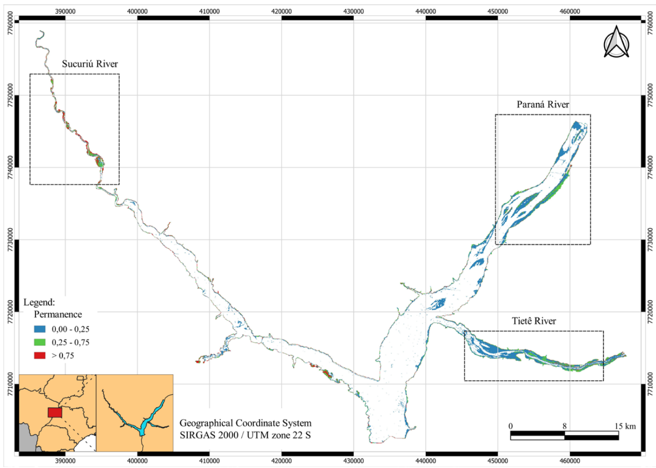

Figure 8. Macrophyte permanence map for the entire period 1984-2021* (*except for the years: 2003, 2011, 2012 and 2013).

For each of these three regions, the permanence was mapped considering seasonal variations and variations over the decades.

In the Tietê River (Figure 9), it is noted from Spring to Summer there is an increase in the occupied area and permanence, while from Summer to Autumn there is an increase in area and a decrease in permanence. From Autumn to Winter, there is a decrease in both area and permanence, while from Winter to Spring there is a reduction in area, but an increase in permanence. This behavior is also described by Esteves (1998) when it is stated that, in general, the primary productivity of the species reaches the highest levels during the Spring, followed by the Summer, when, at the end of this season, the formation of debris begins, for by the end of Autumn the community is practically dead. These last two behaviors (from Summer to Autumn and from Winter to Spring) were also observed in a branch of the Itaipu reservoir, located about 550 km downstream from Jupiá (Rosa et al., 2018). It is also noteworthy there are regions in left bank which present intermediate permanence throughout all seasons, which may indicate regions of active renewal of these organisms (such as macrophyte nurseries) (Figure 9).

Likewise, for the variation between decades, the general behavior over the years was an increase in occupied area and permanence. In the 1980s there was a predominance of macrophytes on the banks reaching high permanence values, while from the 1990s the area extends to the center of the channel. Subsequently, in the 2000s, there was a clearer delimitation of macrophyte areas (such as island formations in the channel center) and an increase in permanence in regions close to the banks. This behavior became

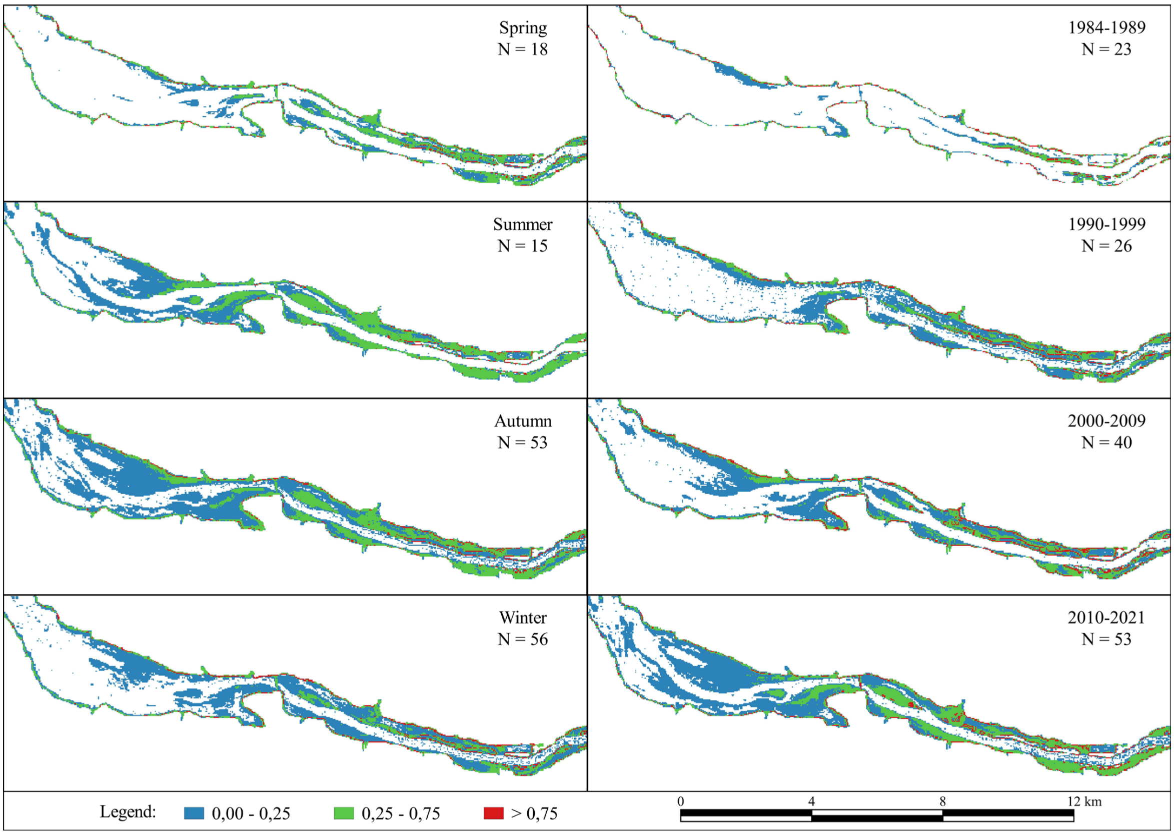

Figure 9. Permanence map detailing for the Tietê River region with variations between seasons and decades.

even more pronounced in the 2010s (Figure 9) and is associated with lower flow velocities that, due to the channel geometry, end up becoming shelters for the development and establishment of these organisms (Thomaz, 2002). This result corroborates another study wherein it was found that the 53% increase in the area of macrophytes in the São Francisco River was observed on the bank with lower speed and depth, rather than on the bank where there is navigation (Minhoni et al., 2018).

Conversely, for the Paraná River (the visualization can be found in the Supplementary Material, Figure SP4), mainly in the region of Ferradura island and for the left bank (considering the river flow direction), from Spring to Summer there is an increase in the area of occupation and a decrease in permanence, while from Summer to Autumn there is a decrease in the area of occupancy and increased permanence. This behavior is repeated from Autumn to Winter and from Winter to Spring (the visualization can be found in the Supplementary Material, Figure SP4). Variations in area and permanence over the decades occurred similarly to the Tietê River, with emphasis on the increase in area on the left bank and on Ferradura island.

Otherwise, in the Sucuriú River the variation is not as pronounced as in the other analyzed regions (the visualization can be found in the Supplementary Material, Figure SP5), both for the variation between seasons and over the decades. Here it is noted that the Summer was the season that presented shorter permanence than others, and in the Spring, there were more areas with high permanence. As for the permanence variation over the decades, despite the areas remaining constant, it is noted the 1990s presented higher permanence for the areas occupied by macrophytes and that this value decreased over the following years, with the 2010s permanence lower than 2000s.

Environmental variables effects on macrophyte growth

After verifying macrophyte area growth trends over time and seasonal variations, some limiting factors to macrophyte growth were analyzed in order to verify if and which environmental variable contributed to these processes.

Land use analysis

For the four basins analyzed (Jupiá basin, and the incremental basins of the Ilha Solteira and Três Irmãos HPP and the Sucuriú River), in general, it was verified a decrease in natural areas of forest and non-forest natural formations (e.g. fields and rock formations) while increasing the coverage of agricultural activities and non-vegetated areas (e.g. urban areas and mining) (Figure 10).

There are some physical and environmental characteristics that influence the growth of macrophytes, for instance, the availability of nutrients - both those disposed in the sediment and those dissolved in the water (Bianchini Junior, 2003; Esteves, 1998; Tundisi & Tundisi, 2008). The incremental basin of the Sucuriú River (with the smallest area) was the one that presented the greatest variation in land use; however, this variation is small when compared to the basin total area (Jupiá). This fact may

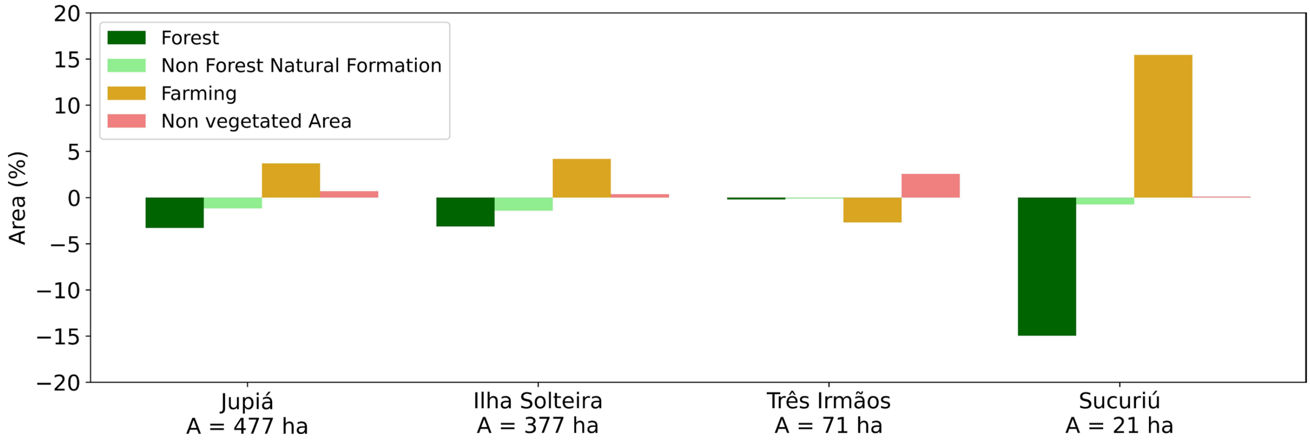

Figure 10. Land uses variation in the Jupiá watershed and in the incremental watersheds (Ilha Solteira, Três Irmãos and Sucuriú) between 1985 and 2020.

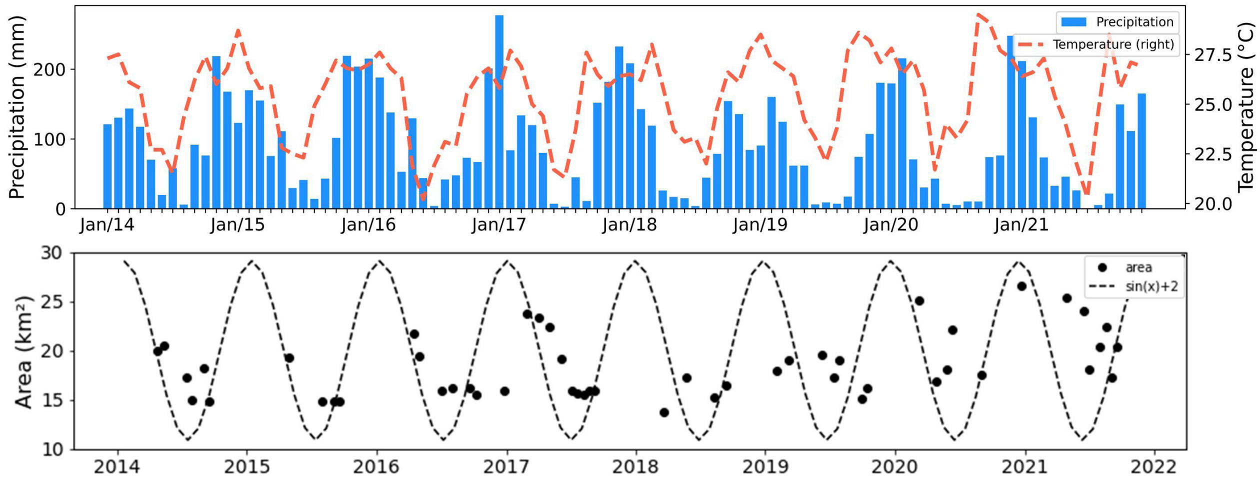

Figure 11. Seasonal variation of monthly precipitation, monthly mean temperature and macrophyte area over 2014-2021.

indicate the presence of agricultural activities in this region is contributing to the high permanence of macrophytes in this reservoir area, in particular.

Macrophyte growth was also associated with nutrient concentration in the Paraíba do Sul River (São Paulo, Brazil) (Lima et al., 2018), but due to population growth and, consequently, to environmental problems caused by it, such as incorrect disposal waste. Meanwhile, Minhoni et al. (2017) raised as a possible reason for 50% macrophytes area increase in Barra Bonita reservoir between 2014 and 2015, the decrease in the reservoir discharge (due to less precipitation in the period). The authors also noticed greater macrophytes agglomeration in places with less water volume and associated this with a greater nutrient's concentration.

Temperature and precipitation analysis

Although Jupiá reservoir is located in a tropical region, the macrophyte area showed similar behavior to macrophyte species from temperate climates over the last 8 years (Figure 11). In general, primary productivity reaches the highest rates during Spring, when shoots appear and, as temperature and solar radiation increase, leaves also develop. During the Summer, productivity is lower than in the previous season, however it's when the highest biomass values are recorded. At the end of this season, the formation of debris begins, and by the end of Autumn the community is practically dead (Esteves, 1998).

This cyclical and seasonal behavior seems to coincide with what was observed in climatological variables such as precipitation (Climate Hazards Group InfraRed Precipitation with Station Data, 2022) and air temperature (Universidade Estadual Paulista "Júlio de Mesquita Filho", 2022), since the availability of light (which is dependent on incident solar radiation and water turbidity, for example) is one of the limiting factors to the growth of macrophytes, due to the impacts photosynthetic processes and higher temperatures act as catalysts (Bianchini Junior, 2003; Esteves, 1998; Tundisi & Tundisi, 2008). However, statistically, pretty low correlations were found between macrophyte area and monthly rainfall ($\varrho = 0.23$) and monthly mean air temperature ($\varrho = 0.14$). Luo et al. (2016) found a significant positive correlation between certain macrophyte species and air temperature, while for another group of species the correlation was pretty low with. The authors found that for this second group, the correlation was higher when the air temperature was moved left one month, which could be an indication that the growth of certain macrophyte species responds quicker to temperature than others, so that the cyclic behavior can be displaced in time.

Upstream HPP discharge analysis

Hydrodynamic and hydrological conditions - either by the variation of levels or by the speed of current, such as by the rainy and dry seasons - are also a limiting factor to macrophytes grow, because they can provide a calm and favorable environment for the development of these organisms (Bianchini Junior, 2003; Esteves, 1998; Tundisi & Tundisi, 2008). When comparing the macrophyte area data with the operational discharge of the plants upstream Jupiá reservoir (China Three Gorges Brasil Energia Ltda, 2022), it is worth highlight the first macrophyte area peak (October/1991) follows the filling (Cestari Junior & Celeri, 1999) and the beginning of the spill (April/1991) of the Três Irmãos reservoir (Figure 12). The interval between these events could be justified by the fact that spill started in a period when naturally there is senescence of these organisms (Autumn) and the macrophyte peak occurs in the season when primary production reaches the highest rates (Spring), as described above.

It was also possible to notice that until October/1991 the variation in the area of macrophytes was low (σ = 1.08 km^2) when compared to the following decades (σ = 1.70 km^2, σ = 1.79 km^2, σ = 3.17 km^2, respectively, 1990, 2000 and 2010) or with the entire period posterior (σ = 2.60 km^2). Furthermore, we also verified that the data up to October/1991 had a better linear fit (R^2 = 0.35) than the data from the later period (R^2 = 0.10), which could indicate that both data sets do not follow the same behavior. Likewise, the formation of the Três Irmãos reservoir may have contributed to the increase in the amount of nutrients in the water, due to the biomass decomposition process inside the reservoir, while the Tietê River damming may have caused the decrease of the downstream current velocity, providing a peaceful and more favorable environment for macrophytes development.

Furthermore, in April/1991 there was also a peak of maximum monthly flows spillway and outflow at Ilha Solteira HPP, and the hourly value recorded ($Q_{out\ max}$ = 23,526 m^3/s e $Q_{spill\ max}$ = 17,000 m^3/s) was the highest of all the historic series.

When it is analyzed the flows from Três Irmãos HPP, there was a peak of maximum monthly flows spillway and outflow in June/2016, with the recorded hourly value ($Q_{out\ max}$ = 5,160 m^3/s and $Q_{spill\ max}$ = 4,795 m^3/s) was the highest of the entire historical series. When it is analyzed the 2017 event, although there was also a peak, the monthly maximum hourly flows ($Q_{out\ max}$ = 3,401 m^3/s and $Q_{spill\ max}$ = 1,799 m^3/s) were lower than those recorded in 2016. Although the effluent volume in 2017 was 23.7% lower than in 2016, in the 2017 event there were consecutive abrupt increases in discharge, the first being at the beginning of the event (1,167 m^3/s in 4h), followed by another 16h later (1,828 m^3/s in 11h) in addition to 2 cycles of decrease and increase (1,209 m^3/s in 2 and 3h, 961m^3/s in 2h and 1,209m^3/s in 4h) 39h after the start of the event (Figure 13).

However, when we consider the inputs through the Paraná River, despite a slight increase in spillway discharge in 2016, in 2017 the outflow discharge remained at the same magnitude (Figure 12).

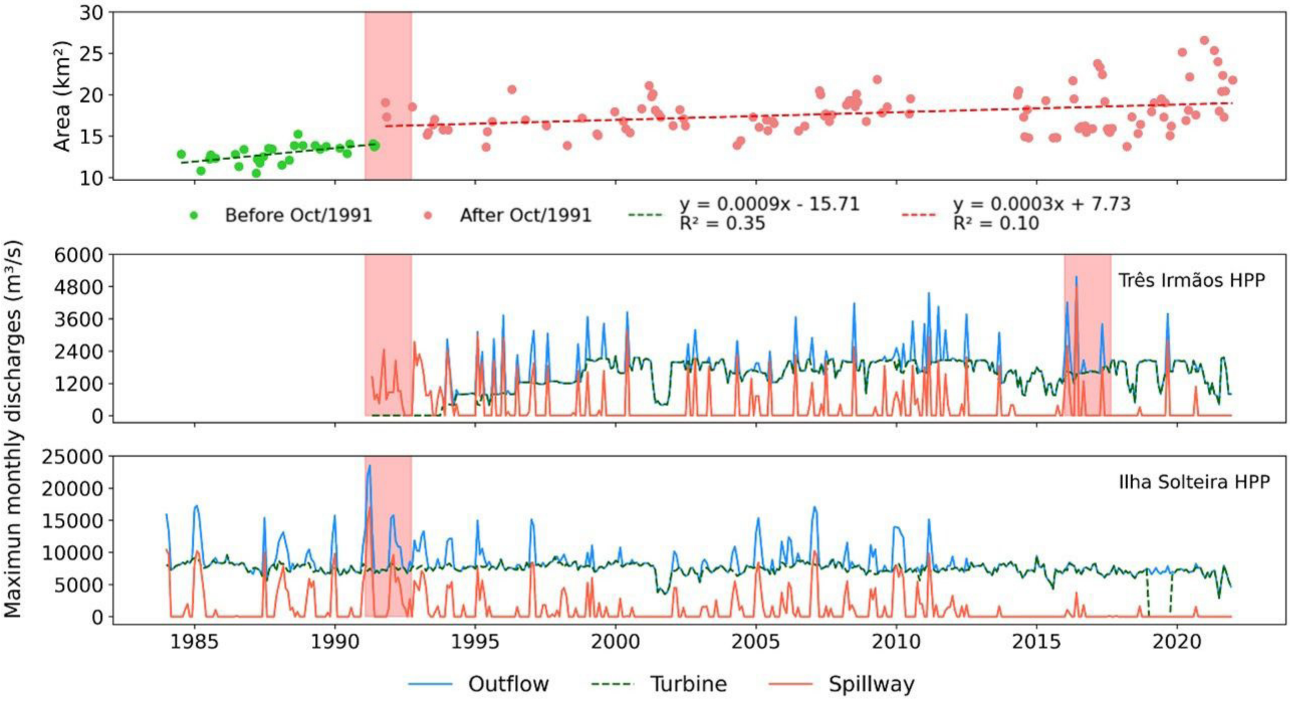

Figure 12. Linear adjustments for the macrophyte area before and after October/1991 and maximum monthly (hourly) outflow, spillway and turbine discharge at Ilha Solteira and Três Irmãos HPP.

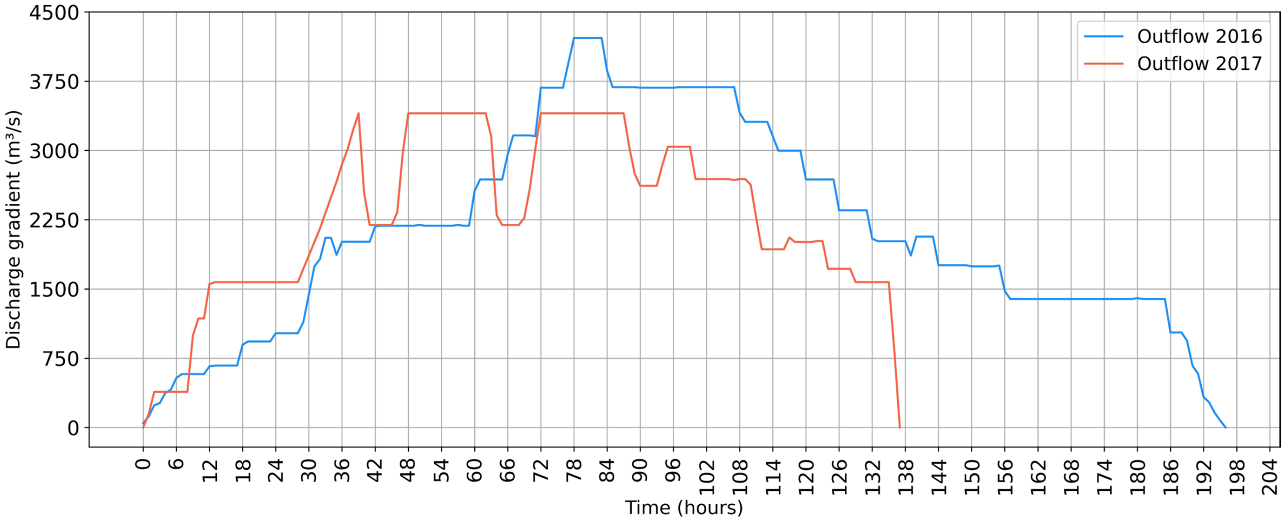

Figure 13. Comparison between June/2016 and May/2017 operations in Três Irmãos HPP.

Considering that: (i) the mapped area close to the date of these two events is similar; (ii) that in terms of total area, they did not stand out throughout the historical series and; (iii) both events happen in Autumn; it is may be possible that the reason why, unlike in 2016, the 2017 event caused impacts both on the spatial arrangement of macrophytes (Figure 9 and Figure 10) on energy generation could be related to the outflow discharge to Jupiá reservoir.

CONCLUSION

In summary, the main advantages of using the GEE platform were, in addition to the vast free image database, the fact that it made it possible to use a significant number of images quickly, since it is not necessary to download them, because their processing is carried out remotely by Google, which also implies that computers with high processing power are not required. Despite the amount of satellite images being a limitation, due to interferences such as sunlight or cloud cover, satellite images used to set up a historical series of macrophyte occupation in the Jupiá reservoir proved to be very satisfactory. This study can be widely expanded to other reservoirs, since nowadays there is still a lack of historical information about their evolution, despite the monitoring of these organisms being a current concern (given the damage caused to energy generation, for example).

The knowledge of the total area and the spatial arrangement of macrophytes over the years allowed us to observe, besides the growth trend, cyclical behaviors coinciding with interannual climatic seasonality, such as detachment and/or death trends of organisms between two consecutive seasons. This information can and should be used as a basis for decision-making regarding monitoring, removal and management of these organisms, thus contributing to ensuring the multiple uses of water.

Another factor to be highlighted is that the outflow discharge on may have caused the displacement of a significant amount of macrophytes from the Tietê River to the Jupiá dam in 2017, causing the interruption of energy generation. Even though the macrophyte mapped area in this event is high, it was not the largest recorded in the entire series. The realization of this fact raises an alert that, as there is a tendency for macrophyte areas to grow (regardless of the interannual variations verified), if in the future there is a need for a similar operation, the severity of the impacts on energy generation also tends to be greater than recorded in 2017.

Although some limiting factors to the growth of macrophytes have been verified, due to the complexity of the interaction of macrophytes with the environment, the use of satellite images to analyze the temporal evolution of physicochemical variables is suggested as a topic for future research, to verify other reasons for the increase in the coverage of macrophytes, especially after the construction of the Três Irmãos reservoir. Furthermore, even though low correlations were found between the macrophyte area and air temperature, it is recommended for future research that the interaction between these variables (or more directly, between water temperature and macrophytes) be studied. deeper, given the cyclical seasonal behavior that both presented.

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Authors contributions

Aline Guidolin da Luz: Literature review, data processing, analysis, and discussion of results and; manuscript writing.

Tobias Bernward Bleninger: Discussion of results and manuscript review.

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Bernardo Lipski: Data processing discussion of results and manuscript review.

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SUPPLEMENTARY MATERIAL

Supplementary material accompanies this paper.

Figure SP1. Vegetation and permanent settlement detailing at Ferradura island, on Paraná River: (A): GSAVI Landsat image (03/05/2017) from the Ferradura island region, on the Paraná River with the sampling points; (B): CNES image (Google Earth Engine, 2022) Vegetation and permanent settlement detailing at Ferradura island, on Paraná River and; (C): Ferradura island field research photographic with large vegetation fixed to the ground and Typha domingensis in the water (05/04/2022).

Figure SP2. Example of errors present in images which were discarded after visual analysis: (A): GSAVI Landsat image (24/11/2010) with sunlight interference in the northern region of the Paraná River; (B): GSAVI Landsat image (24/11/2010) with erroneous macrophytes classification due to sunlight interference in the northern region of the Paraná River, and; (C): GSAVI Landsat image (28/08/1984) which did not contemplate the entire region of the Jupiá reservoir, in addition to presenting a more attenuated color (shades of green) in comparison to A.

Figure SP3. Fit of macrophyte and others vegetation data to normal distributions. The upper limit of each index was obtained at the point where the probabilities of the curves were equal, and the lower limit was determined at the value where 90% of the data were encompassed.

Figure SP4. Permanence map detailing for the Paraná River region with variations between seasons and decades.

Figure SP5. Permanence map detailing for the Sucuriú River region with variations between seasons and decades.

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