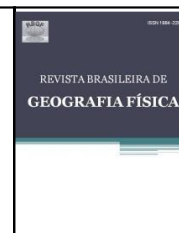




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Detection and Mapping of Eutrophication and Aquatic Plants in a River in the Northeast Region of Brazil Using Sentinel-2 Data

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ABSTRACT

The urban expansion of Teresina has caused environmental impacts on the Poti River due to the occurrence of eutrophication and proliferation of aquatic plants in the dry season of the year. Considering the characteristics related to water-quality monitoring in the Northeast region of Brazil, from remote sensing, this study aimed to evaluate the performance of semi-empirical algorithms in Sentinel-2 data in the detection and mapping of eutrophication and aquatic plants in the river Poti in Teresina, Piauí, Brazil. The eutrophication detection methodology involved the study of the reflectance of the water surface in the Sentinel-2 images and the respective correlation within situ data of chlorophyll-a, using the MCI, MPH and NDCI indexes. The NDCI index showed superior one-off performance than the MCI and MPH indexes. In this sense, with the NDCI, the spatio-temporal variation of eutrophication in the Poti River was identified broadly and no longer specific. In relation to aquatic plants, the NDVI index proved to be appropriate for the detection and mapping of water hyacinths, demonstrating the location of the areas covered by aquatic plants. At the beginning of proliferation, the maximum expansion rate of 854.7% was evaluated. At the end of the dry period, there was a peak of covered area of 570,145.6 m² and a production of 6,408.4 tons of fresh biomass from water hyacinths. Therefore, in both cases, it was found that the MSI sensor was suitable for the detection, mapping and monitoring of eutrophication and aquatic plants in the Poti River.

Keywords: chlorophyll-a, Poti river, remote sensing, water hyacinth.

Detecção e Mapeamento da Eutrofização e Plantas Aquáticas em um Rio na Região Nordeste do Brasil Usando Dados Sentinel-2

RESUMO

A expansão urbana de Teresina tem causado impactos ambientais no rio Poti devido à ocorrência de eutrofização e proliferação de plantas aquáticas na estação seca do ano. Considerando as características relacionadas ao monitoramento da qualidade da água na região Nordeste do Brasil, a partir do sensoriamento remoto, este estudo destinou-se a avaliar o desempenho de algoritmos semiempíricos em dados Sentinel-2 na detecção e mapeamento da eutrofização e de plantas aquáticas no rio Poti em Teresina, Piauí, Brasil. A metodologia de detecção da eutrofização envolveu o estudo da reflectância da superfície da água nas imagens Sentinel-2 e a respectiva correlação com dados in situ de clorofila-a, por meio dos índices MCI, MPH e NDCI. O índice NDCI apresentou melhor desempenho pontual que os índices MCI e MPH. Neste sentido, com o NDCI, foi identificada a variação espaço-temporal da eutrofização no rio Poti de maneira ampla e não mais pontual. Em relação às plantas aquáticas, o índice NDVI se mostrou apropriado para a detecção e mapeamento dos aguapés, demonstrando a localização das áreas cobertas pelas plantas aquáticas. No início da proliferação foi avaliada a taxa de expansão máxima de 854,7%. No final do período seco ocorreu um ápice de área coberta de 570.145,6 m² e uma produção de 6.408,4 toneladas de biomassa fresca de aguapés. Portanto, nos dois casos, constatou-se que o sensor MSI foi adequado para a detecção, mapeamento e monitoramento da eutrofização e de plantas aquáticas no rio Poti.

Palavras-chave: aguapé, clorofila-a, rio Poti, sensoriamento remoto.

Introduction

Inland waters are aquatic environments typically confined within the boundaries of the land, such as lakes, reservoirs, rivers, ponds, swamps and wetlands, that serve as signs of changes in the environment, such as climate change, as well as land use and cover (Ogashawara et al., 2017; Martins, 2019).

In the world, eutrophication has become the main issue in the reduction of water quality, since it restricts its multiple uses, and can pose a serious threat to the health of animals and humans. This is a phenomenon characterized by the enrichment of water, caused by natural or anthropogenic sources of nutrients, which results in a decrease in species diversity and an increase in the growth of; phytoplankton, algae, cyanobacteria and aquatic plants (Khan and Mohammad, 2014; Boyd, 2020).

Chlorophyll-a; a photosynthetic green pigment present in photoautotrophic bacteria and plants, emerges as one of the main indicators of water quality, biophysical status, and the level of eutrophication of a body of water (Ha et al., 2017; Matthews, 2017; nsper and Alikas, 2019), in addition to being used to detect the proliferation of algae (Pereira-Sandoval et al., 2019), cyanobacteria (Mishra et al., 2020) and aquatic plants (Singh et al., 2020). Rivers are an important source of highly dynamic freshwater, varying spatially and temporally. Regular monitoring of these ecosystems is increasingly necessary to broaden the understanding of biogeochemical processes and to accompany rapid environmental changes. Remote sensing provides a solution for continuous and large-scale monitoring and mapping of these environments (Barret and Frazier, 2016; Martins, 2019; Prasad et al., 2020). Thus, satellites are tools for rapid, frequent, synoptic detection of dynamic, undersampled locations with limited access, which reduces the costs of monitoring and preventing water quality degradation (IOCCG, 2018; Page et al., 2018).

The Copernicus Sentinel-2 Program developed by the European Space Agency (ESA) comprises of a constellation with the satellites in polar orbit Sentinel-2A and Sentinel-2B with high temporal resolution of 5 days. The main objectives of the mission are to monitor the conditions of use and coverage of the Earth, climate change and disasters, with a policy of free access. The MultiSpectral Instrument (MSI) has radiometric resolutions of 13 spectral and spatial bands of 10m, 20m and 60m (ESA, 2021; Phiri et al., 2020).

The use of Sentinel-2 data and in situ observations, combined through the use of semi-empirical bio-optical algorithms to estimate the

concentration of chlorophyll-a and aquatic plants in inland waters, are based on statistical analysis between radiometric data from the sensors satellites and measurements of parameters of water and plant constituents. The combination of spectral bands follow specific physical bases reasoned on the spectral behaviour and biological activity of the target, with results correlated to biological activity through statistical analysis (Morel, 2001; Ogashawara et al., 2017; Barbosa, 2019).

Therefore, the studies usually address the combination of spectral bands in the blue and green, red and green, red and near infrared regions, for the mapping of chlorophyll-a (Mouw et al., 2015; Toming et al., 2016; Ha et al., 2017). In the case of aquatic plants, the bands are in the blue, red, near infrared, red border 1, short wave infrared 1 and 2 (Thamaga and Dube, 2018; Ghoussein et al., 2019; Dersseh et al., 2020).

The process of accelerated and disordered growth in the city of Teresina, located in the Northeast region of Brazil, has caused environmental problems that affect the Poti River, such as eutrophication and the appearance of proliferation of phytoplankton, algae, cyanobacteria and aquatic plants that have occurred, notably, since 2003, in the dry period of the year (Brazil, 2007; Costa, 2014; Santos, 2017). In a recent study, researchers from the Environmental Sanitation Laboratory of the Federal University of Piauí (UFPI), estimated the concentration of chlorophyll-a in seven points located on the Poti riverbed, during the proliferations that occurred in the years 2016 and 2017 (Soares et al. 2019; Pereira et al., 2020). However, in 2019, there was a great proliferation of aquatic plants, especially water hyacinths or *Eichhornia crassipes* (Bom Dia Piauí, 2019).

In this context, and considering that chlorophyll-a sampling is a high-cost process, the use of remote sensing can monitor water quality parameters and aquatic plants in multiple stretches of the Poti River, in different time periods and with reduced costs, because there is an association between chlorophyll-a concentration data, obtained in situ and by bio-optical algorithms. Therefore, the present study aims to evaluate the performance of semi-empirical band ratio algorithms in Sentinel-2 satellite data in the detection and mapping of chlorophyll-a concentration, in the years 2016 and 2017, and aquatic plants, in 2019, in the urban bed of the Poti River, in Teresina, Piauí, Brazil, with the perspective of contributing to the conservation of the environment and sustainable management of this water resource.

Material and methods

Study area

The study area corresponds to the 36.8 km urban stretch along the Poti River, located in Teresina, Piauí, Brazil. As reported by Pereira et al. (2020); the Environmental Sanitation Laboratory, Federal University of Piauí, carried out monthly sampling of chlorophyll-a concentrations at seven monitoring points located on the Poti riverbed, in 2016 and 2017. The collection points are in easily accessible places, as well as in regions with little urban intervention or more urbanized on the Poti River in Teresina.

It is important to highlight that the chosen area becomes a lentic environment, in the dry period of the year, different from the lotic condition of the rainy season. It should be noted that according to the Brazilian Climatological Standard 1981-2010, the dry period in Teresina occurs between the months of June to November. The average temperature, relative humidity and precipitation, in the dry period of 2016 and 2017,

were, respectively, 29.2°C, 52.3% and 10.7 mm (INMET, 2018).

Figure 1 and Figure 2 shows the spatial distribution and panoramic view of the monitoring points, where from the point PT-05, upstream (south) and downstream (north), the extensive proliferation of aquatic plants, especially water hyacinths was observed, on October 31, 2019.

According to the National Water and Basic Sanitation Agency (ANA, 2019), the Poti River micro basin, in the Teresina region presents a qualitative criticality that results from the degradation of water quality, due to the release of domestic effluents and inadequate water management practices and deposition of solid waste. The proportion of water bodies with good water quality in the Parnaíba Hydrographic Region, which encompasses the Poti River, reached 68.2%. In addition, according to ANA, the good condition considers the class 2 limits of the water quality standards of rivers and reservoirs, defined in Resolution nº 357/2005 of the National Environment Council (CONAMA, 2005).

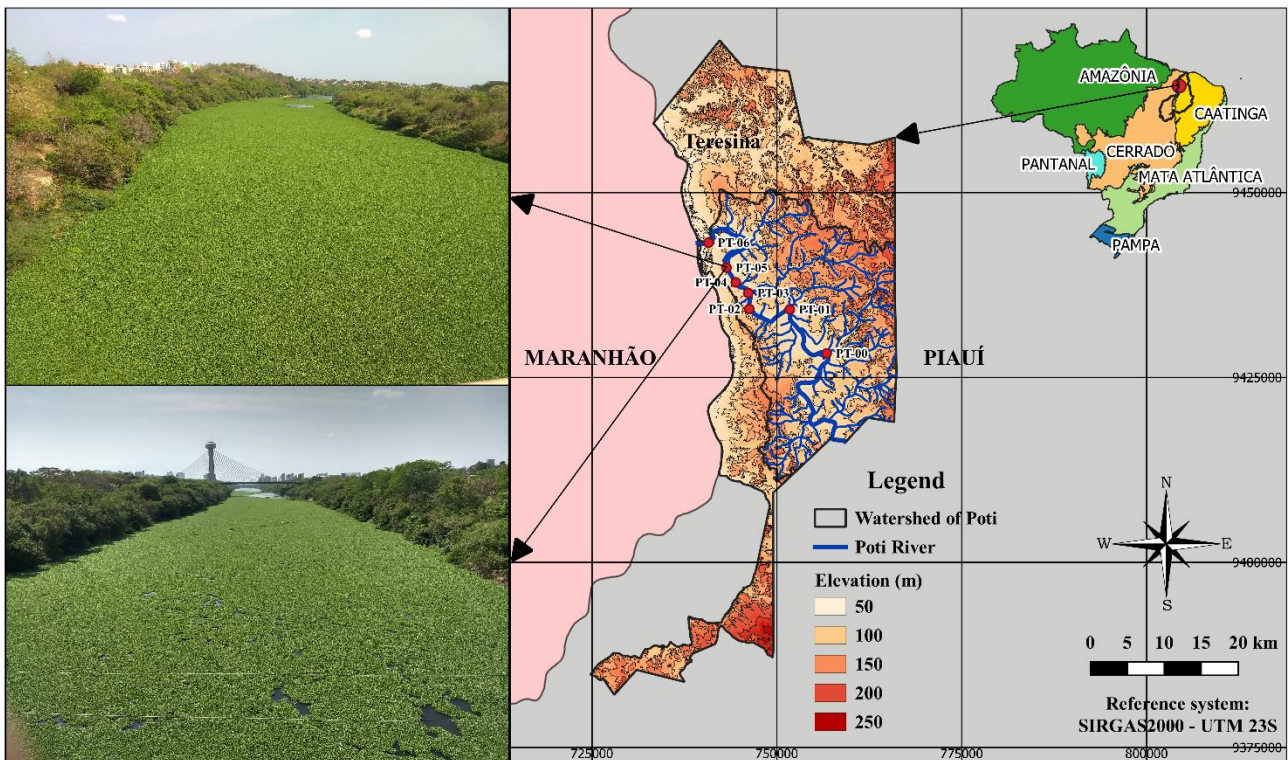


Figure 1. Study area: Location of Teresina in the context of Brazil's biomes Cerrado and Caatinga (MMA, 2017), as well as the watershed of the Poti River in Teresina, with its limits and hydrography (ANA, 2017), obtained altimetry the SRTM digital elevation model (USGS, 2019) and position of the monitoring points.

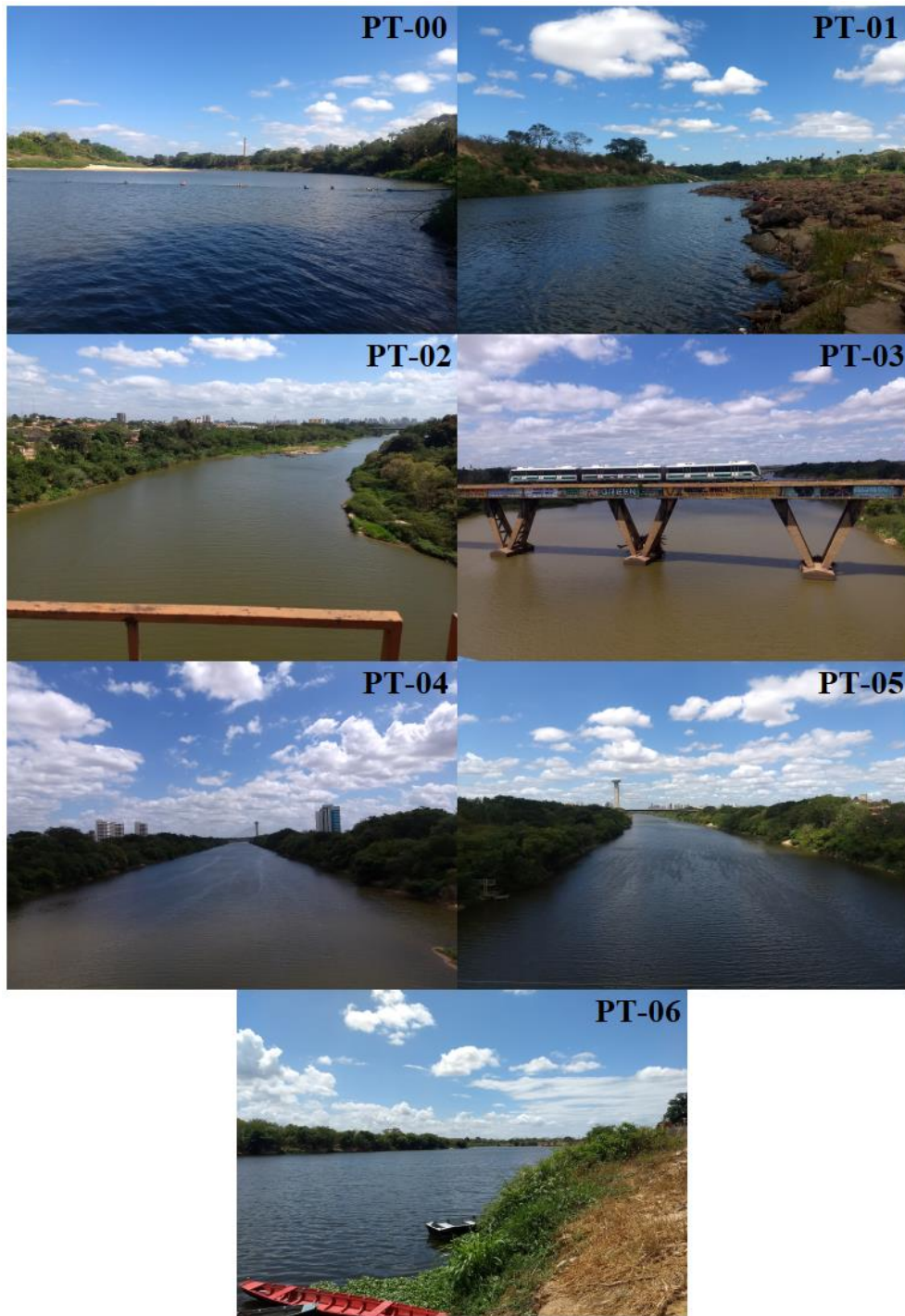


Figure 2. Panoramic view of the points in the study area on August 15, 2019.

Remote sensing data acquisition and pre-processing

The data from the Sentinel-2, A and B satellites, orbit 138, were acquired on the Copernicus Open Access Hub digital platform (ESA, 2022). The products Level-1C (L1C), from 2016 and 2017, and Level-2A (L2A), from 2019, are pre-processed with Top-of-atmosphere (TOA) and Bottom-of-atmosphere (BOA) radiometric corrections, respectively, as well as orthorectified, georeferenced (ESA, 2021). The atmospheric correction in the L1C product was performed with the Sen2Cor-2.8 processor, available in the toolbox

of the Sentinel Application Platform program, resulting in the L2A product. The specifications for the Sentinel-2, A and B satellite bands are shown in Table 1 (ESA, 2021, 2022).

To explore the concentration of chlorophyll and the proliferation and aquatic plants, the following data sets were formed, respectively: i) eight products level L1C, considering the dates of Pereira et al. (2020); ii) six L2A level products, with the following acquisition dates: September 14, 2019 and October 14, 2019, from Sentinel-2B; October 29, 2019, November 8,

2019, December 8, 2019, and December 28, 2019, of Sentinel-2A.

Chlorophyll-a recovery algorithms

The recovery of chlorophyll-a concentration was based on a literature review, in which the semi-empirical bio-optical algorithms Maximum Chlorophyll Index (MCI), Maximum Peak-Height (MPH) and Normalized Difference Chlorophyll Index (NDCI), presented in the Equations, were selected 1, 2 and 3, simultaneously. The indices included the blue, green, and red bands and those that include the red

border band. These indices showed the best performances in estimating chlorophyll-a in Sentinel-2 images, in inland waters of regions with similar geographical and climatic characteristics to those found in Teresina (Matthews, 2017; Xu et al., 2019; Peppia et al., 2020). Thus, the following steps were performed in the QGIS 3.4.5 software: i) Calculation of the concentration of chlorophyll-a, according to the MCI, MPH and NDCI indices; ii) List of chlorophyll-a values at monitoring points. The selection of the Sentinel-2A band followed the criterion of proximity to the wavelength closest to that defined in each index.

Table 1. Sentinel-2A and Sentinel-2B satellite band specifications.

Band Number	Band Name	Central wavelength S2-A	Central wavelength S2-B	Uses of the MSI sensor
B04	Red	664,6 nm	664,9 nm	Identify vegetation types, soils and urban (city and town) areas
B05	Red edge 1	704,1 nm	703,8 nm	Classify vegetation
B06	Red edge 2	740,5 nm	739,1 nm	Classify vegetation
B08	Near infrared (NIR)	832,8 nm	832,9 nm	Map coastline and biomass content; detect and analyze vegetation
B08A	Red edge 4	864,7 nm	864,0 nm	Classify vegetation

The differences between punctual chlorophyll-a concentrations, in situ (Chla-is) and satellite-derived (MCI, MPH, NDCI), were quantified, in the programs R 3.6.1 and Past 3.24, using the following statistical metrics: coefficient of determination (R²), the Root Mean Square Error (RMSE) and the Bias (Ha et al., 2017; Qin et al., 2017; Page et al., 2018).

$$MCI = B05 - 1.005 \left(B04 + \left((B06 - B04) \times \left(\frac{\lambda_{B05} - \lambda_{B04}}{\lambda_{B06} - \lambda_{B04}} \right) \right) \right) \quad (1)$$

$$MPH = B05 - B04 - \left((B08A - B04) \times \left(\frac{\lambda_{B05} - \lambda_{B04}}{\lambda_{B08A} - \lambda_{B04}} \right) \right) \quad (2)$$

$$NDCI = (B05 - B04) / (B05 + B04) \quad (3)$$

In situ data of chlorophyll-a, total phosphorus and determination of trophic status index

It is noteworthy that in this study the same 56 samples of chlorophyll-a are used in situ and the same eight L1C products from the Sentinel-2A satellite, arranged in Pereira et al. (2020). Therefore, there are the same number of match-ups

that varied with a difference of one to twelve days, in all the period available in the dry season.

The phosphorus sampling campaigns were carried out in conjunction with the chlorophyll-a samplings, as well as following the standards established in the National Guide for the Collection and Preservation of Samples of the National Water Agency (ANA) and in CONAMA Resolution n° 357/2005. The phosphorus samples were filtered, extracted and calculated by the colorimetric method (APHA, 2005).

To classify the Poti River at different levels of eutrophication or degrees of trophic, the Trophic State Index (TSI) with the parameters chlorophyll-a (Cl) and total phosphorus (TP) was used. The equations for calculating the TSI (Cl), Equation 4, and TSI (TP), Equation 5, in rivers are in line with (Lamparelli, 2004).

$$TSI(Cl) = 10 \times (6 - ((-0,7 - 0,6 \times \ln(Cl)) / (\ln(2)) - 20)) \quad (4)$$

$$TSI(TP) = 10 \times (6 - ((0,42 - 0,36 \times \ln(TP)) / (\ln(2)) - 20)) \quad (5)$$

The results presented by TSI, represent the simple arithmetic mean of the indices related to chlorophyll-a and total phosphorus, according to Equation 6 (CETESB, 2020).

$$TSI = [TSI(Cl) + TSI(TP)] / 2 \quad (6)$$

The TSI (TP) is a measure of the potential for eutrophication since phosphorous acts as the causative agent of the process. The TSI (CI) is a measure of the response of the water body to the causative agent, indicating the level of growth of algae that takes place in its waters. Thus, the TSI encompasses the cause and effect of the process (CETESB, 2020).

Soon after, the results of the index are compared with the trophic levels, that is, the productivity of the ecosystem.

Table 2 shows the specific limits and their respective characteristics, defined according to the water quality standards of rivers determined in CONAMA Resolution No. 357/2005 (Lamparelli, 2004, CETESB, 2020).

Vegetation recovery algorithm

One way of identifying vegetation in aquatic environments is using vegetation indices, which are dimensionless radiometric measurements, these indices indicate the activity of green vegetation, adding to the leaf area index, percentage of green cover, chlorophyll content and green biomass (Jensen, 2014). The Normalized Difference Vegetation Index (NDVI), Equation 7, is a semi-empirical bio-optical algorithm widely used in Sentinel-2 images, to estimate the area covered by aquatic plants in rivers and lakes, normalizing the dispersion of green leaves at

wavelengths near infrared, with chlorophyll absorption in the red wavelengths (Ghoussein et al., 2019; Dersseh et al., 2020).

$$NDVI = (B08 - B04)/(B08 + B04) \quad (7)$$

To estimate the expansion rate of aquatic plants (AP), specifically the maximum monthly expansion rate, a calculation was made, considering the coverage areas, both in the current month (CM) and previous month (PM). The classification was focused only on the limits of the Poti River and did not include riverside vegetation. The monthly expansion rate of aquatic plants was calculated by comparing the coverage of aquatic plants in successive months (Dersseh et al., 2020), according to Equation 8.

$$\left(\frac{AP \text{ area in the CM} - AP \text{ area PM}}{AP \text{ area PM}} \right) \times 100\% \quad (8)$$

In order to assess the fresh biomass of water hyacinths in situ at the end of the dry period, a sample of the plant was manually collected with the aid of a square structure, made of wood and with an area of 25 m². Weighing was carried out on a digital scale, with a precision of one decimal place (Figure 3). It should be noted that due to the average dimensions of the plants, being around 0.5 m, it became impossible to use lengths less than 5 m for the sides of the wooden structure.

Table 2. TSI classification (mg / m³) for rivers, of which each class of trophic state is represented by defined colours.

Trophic State	Weighting	Characteristics
Ultraoligotrophic	TSI ≤ 47	Clean water bodies with very low productivity
Oligotrophic	47 < TSI ≤ 52	Clean water bodies with low productivity
Mesotrophic	52 < TSI ≤ 59	Bodies of water with intermediate productivity
Eutrophic	59 < TSI ≤ 63	Bodies of water with high productivity and increased concentration of nutrients
Supereutrophic	63 < TSI ≤ 67	Bodies of water with high productivity and episodes of algal blooms
Hypereutrophic	TSI > 67	Water bodies affected by high concentrations of organic matter and nutrients



Figure 3. Wooden structure and the procedure of weighing water hyacinths.

Results and discussion

Comparison of chlorophyll-a concentrations

The performance of the MCI, MPH and NDCI indices were analysed punctually, from the Sentinel-2A satellite images, because depend on the optical properties of the river and chlorophyll-a, light, temperature and nutrients. These indices tend to vary in performance and may introduce

classification errors (Xu et al., 2019; Peppas et al., 2020). In our study, we divided the 56 sampling points into two sets: 2016 and 2017. Therefore, four values of chlorophyll-a were used for each sampling point. The performances of the semi-empirical algorithms for the Poti River, in 2016 and 2017, are summarized in Table 3.

Table 3. One-off comparison between the estimated and in situ concentration of chlorophyll-a (mg / m³) in 2016 and 2017.

Point / Year	MCI			MPH			NDCI		
	R ²	RMSE	Bias	R ²	RMSE	Bias	R ²	RMSE	Bias
PT-00/16	0.74	113.30	-112.94	0.01	47.15	-40.49	0.19	22.33	17.71
PT-01/16	0.05	116.27	-98.82	0.16	109.69	-90.30	0.01	38.60	31.27
PT-02/16	0.04	148.58	-128.76	0.02	146.54	-121.93	0.09	42.31	32.54
PT-03/16	0.97	220.42	-193.49	0.98	219.72	-196.67	0.97	24.02	22.96
PT-04/16	0.98	288.90	-271.73	0.92	324.24	-302.59	0.50	43.30	39.24
PT-05/16	0.05	285.38	-260.61	0.05	352.52	-307.57	0.52	31.91	28.31
PT-06/16	0.01	295.57	-264.32	0.00	323.11	323.11	0.02	34.53	27.04
PT-00/17	0.16	93.81	-13.58	0.98	16.60	13.46	0.00	5.50	5.20
PT-01/17	0.31	87.62	-77.29	0.00	58.23	-45.39	0.03	12.40	10.32
PT-02/17	0.39	151.36	-147.86	0.76	121.51	-116.63	0.97	18.81	18.81
PT-03/17	0.19	126.26	-120.81	0.37	100.27	-92.87	0.25	11.42	9.20
PT-04/17	0.72	131.63	-128.84	0.64	110.41	-104.45	0.59	11.37	9.16
PT-05/17	0.44	124.12	-113.17	0.60	113.64	-103.84	0.96	10.77	10.17
PT-06/17	0.01	216.74	-199.20	0.49	257.37	-236.02	0.15	12.79	11.20

Considering a moderate correlation, with R² values equal to or greater than 0.50, the MPH and NDCI indices obtained six values, while the MCI index obtained four values. Therefore, the NDCI index obtained the best point performance compared to the MPH index, since the bias values were closer to zero, demonstrating a small systematic overestimation of the chlorophyll-a concentration estimated by Sentinel-2 data and in situ data. According to these results, the relationship between the B04 and B05 bands, is the most suitable for the recovery of chlorophyll-a in the Poti River, which is in conjunction with observations made by Pereira et al. (2020). NDCI

values obtained from the Sentinel-2 showed good results in the Tietê River Basin (Lobo et al., 2021).

The increase in chlorophyll-a concentrations is due to variations in the composition and physiology of phytoplankton species present in this environment, and the increase in cyanobacteria biomass, which become dominant, especially in the dry period. This demonstrates possible adjustments of these phytoplankton communities to the environmental conditions existing over time, as observed by Soares et al. (2019).

Mapping of eutrophication levels

The mapping of chlorophyll-a concentrations was carried out in QGIS 3.4.5, in which a cutting out of the image was created for the study area, in the resulting images from each calculated equation. Figure 4 e Figure 5 shows the change in chlorophyll-a concentration at the beginning of the dry season, from August 2016 to November 2017, calculated with data from the

NDCI index. In the figures, the high concentration of chlorophyll-a corresponds to red.

The maps derived from Sentinel-2A-L2A allow the identification of areas with high or low concentrations of chlorophyll-a and, again, show that the stretch from point PT-04 to the mouth of the Poti River, remains as the area that presents the largest concentrations of chlorophyll-a, according to a study by Pereira et al. (2020).

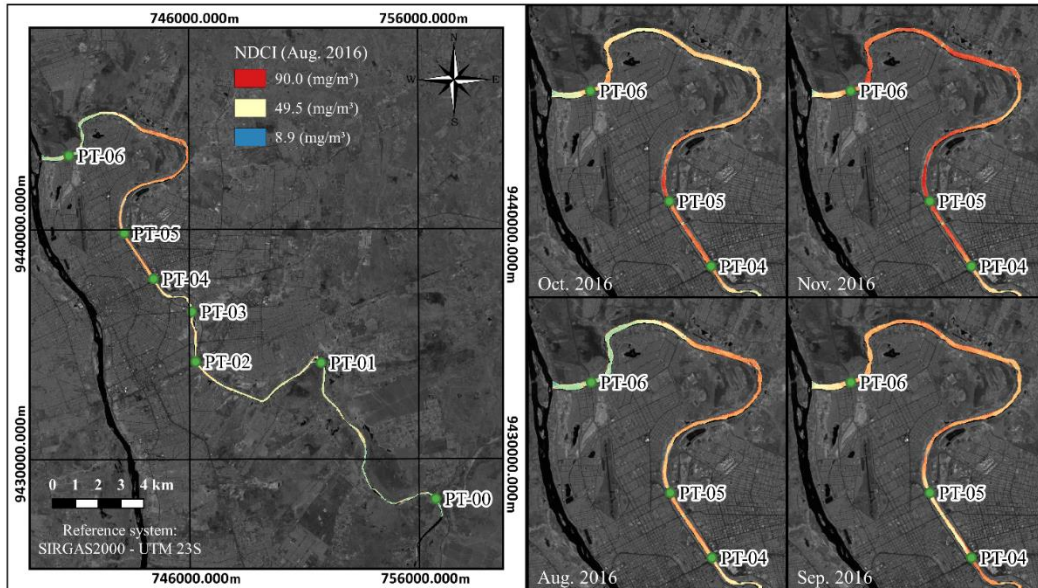


Figure 4. Spatial distribution of chlorophyll-a concentration from August to November 2016.

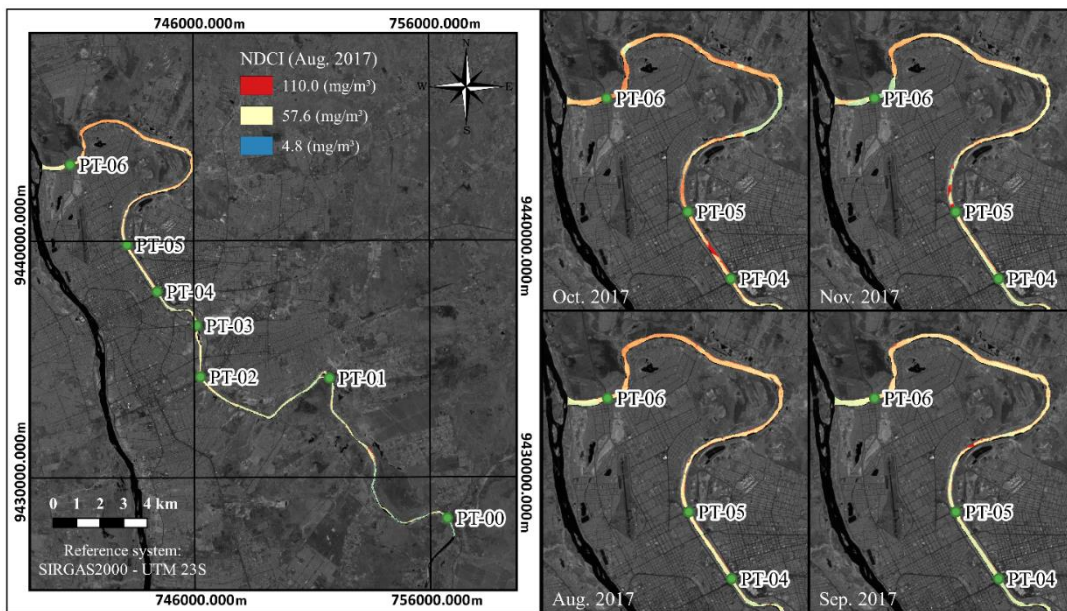


Figure 5. Spatial distribution of chlorophyll-a concentration from August to November 2017.

Classification of trophic status index

The results of the TSI and trophic levels for the monitored points are shown in Table 4 and Table 5. The values indicated that the Poti River section presented good water quality, with the predominance of low potential for eutrophication

development in the seven monitoring points. In addition, it is clear that the TSI (CI), that is, chlorophyll-a is the agent that most contributed to the establishment of the TSI.

Considering CONAMA Resolution 357/2005, regarding the classification of bodies of

water, the samples of chlorophyll-a and phosphorus met the conditions and standards of Class 2, for fresh water, which are intended for supply of human and animal consumption and protection of aquatic communities primary contact recreation, irrigation, aquaculture and fishing activity (CONAMA, 2005).

Considering the results for the TSI, the following trophic states are observed in 2016: Ultraoligotrophic in 13 samples (46.4%);

Oligotrophic in 12 samples (42.9%); and Mesotrophic in 3 samples (10.7%). In 2017, only the ultraoligotrophic state was obtained in the 28 samples. Thus, in general, the results point to the predominance of the lowest degree of trophic, ultraoligotrophic in 41 samples (73.2%), followed by variations in the oligotrophic classes in 12 samples (21.4%) and mesotrophic in 3 samples (5.4%), throughout the dry period of that biennium.

Table 4. Classification of the Poti River according to the TSI (mg / m³) in 2016.

Ponto	TSI	August	September	October	November
PT-00	TSI-CI	64.79	64.79	81.64	76.79
	TSI-TP	12.46	15.18	14.78	14.78
	TSI	38.63	39.99	48.21	45.79
PT-01	TSI-CI	86.30	70.79	81.64	70.79
	TSI-TP	17.35	19.06	19.90	19.90
	TSI	51.83	44.93	50.77	45.35
PT-02	TSI-CI	87.64	80.30	64.79	74.30
	TSI-TP	17.09	15.73	17.09	17.09
	TSI	52.36	48.02	40.94	45.70
PT-03	TSI-CI	74.30	78.72	74.30	80.30
	TSI-TP	18.78	14.99	15.73	15.73
	TSI	46.54	46.85	45.02	48.02
PT-04	TSI-CI	86.99	80.30	78.72	78.72
	TSI-TP	21.55	20.20	20.82	20.82
	TSI	54.27	50.25	49.77	49.77
PT-05	TSI-CI	78.72	82.79	64.79	81.64
	TSI-TP	18.68	21.08	21.66	21.66
	TSI	48.70	51.93	43.23	51.65
PT-06	TSI-CI	70.79	85.55	80.30	64.79
	TSI-TP	17.60	19.15	20.69	20.69
	TSI	44.20	52.35	50.50	42.74

Table 5. Classification of the Poti River according to the TSI (mg / m³) in 2017.

Ponto	TSI	August	September	October	November
PT-00	TSI-CI	62.41	62.41	62.41	68.41
	TSI-TP	5.26	15.90	14.35	15.73
	TSI	33.83	39.15	38.38	42.07
PT-01	TSI-CI	62.41	76.34	62.41	71.91
	TSI-TP	6.42	15.90	15.37	14.78
	TSI	34.41	46.12	38.89	43.35
PT-02	TSI-CI	71.91	80.41	71.91	62.41
	TSI-TP	7.37	16.38	16.38	15.55
	TSI	39.64	48.39	44.15	38.98
PT-03	TSI-CI	62.41	62.41	76.34	68.41
	TSI-TP	8.86	16.06	14.78	15.73
	TSI	35.63	39.23	45.56	42.07
PT-04	TSI-CI	68.41	62.41	76.34	62.41
	TSI-TP	10.02	15.90	17.09	15.37
	TSI	39.21	39.15	46.71	38.89
PT-05	TSI-CI	68.41	68.41	74.41	68.41
	TSI-TP	10.97	16.38	18.59	18.38
	TSI	39.69	42.39	46.50	43.39
PT-06	TSI-CI	62.41	68.41	71.91	76.34

TSI-TP	9.48	15.18	18.06	15.73
TSI	35.94	41.79	44.99	46.03

Mapping of the area colonized by aquatic plants

The mapping of the proliferation of aquatic plants was carried out in QGIS 3.4.5. The maps, shown in the Figure 6, Figure 7 and Figure 8 allow the identification of areas with the presence of plants, showing the spatio-temporal variation of the proliferation determined with the NDVI index. It

appears that the green carpet of water hyacinths reached its peak at the end of the dry period, in December, in the stretch from the Parque Ambiental Floresta Fossil, (a natural dam that consists of a rocky outcrop in the Poti riverbed that reduces its width and depth), to the mouth, at the confluence of the Poti and Parnaiba Rivers.

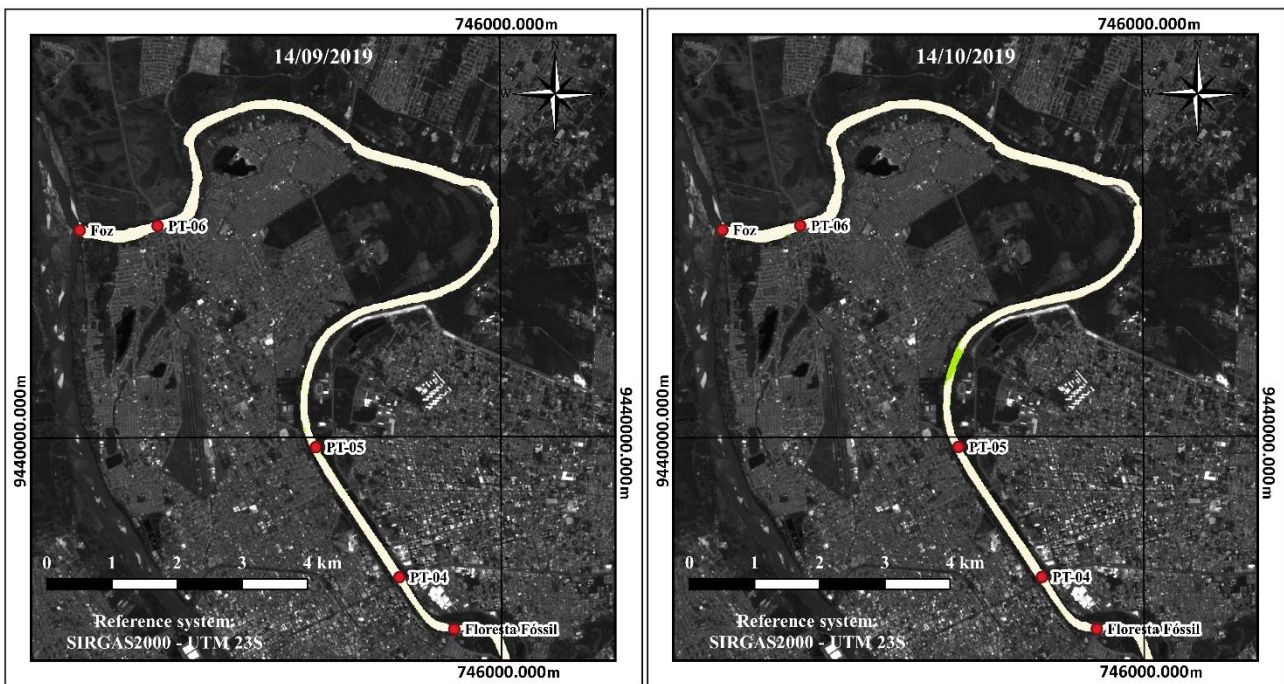


Figure 6. Spatial distribution of aquatic plant proliferation in September and October 2019.

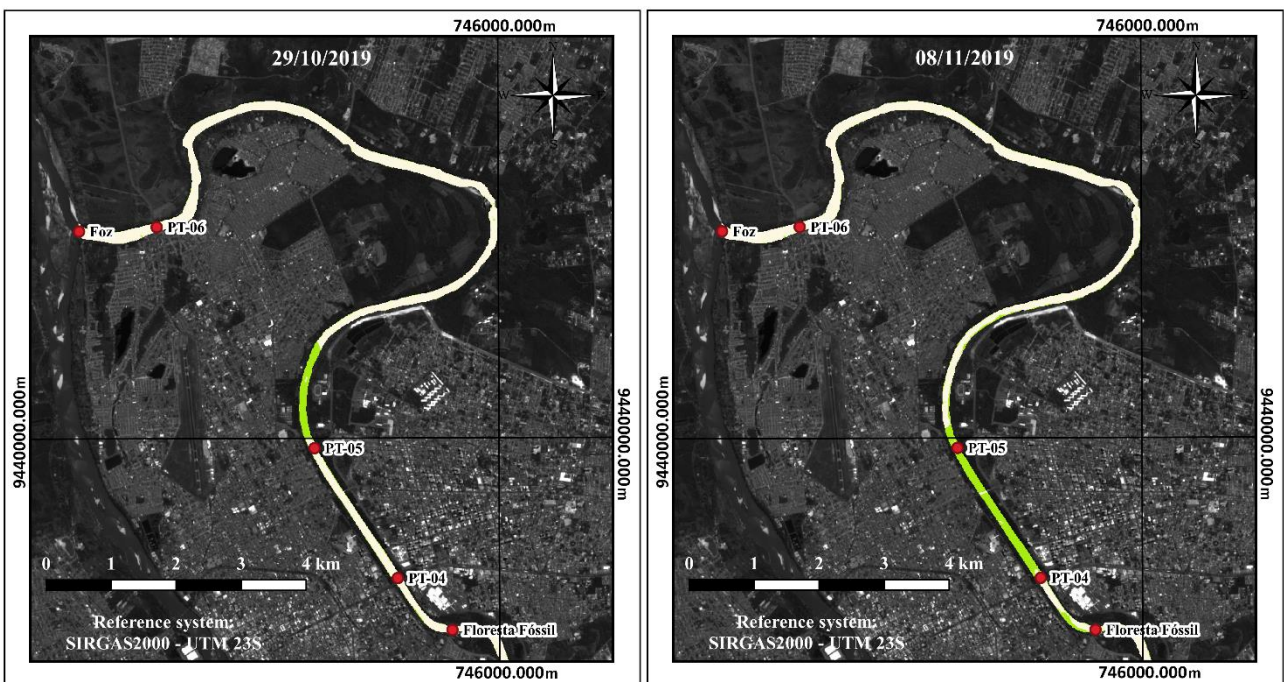


Figure 7. Spatial distribution of aquatic plant proliferation in October and November 2019.

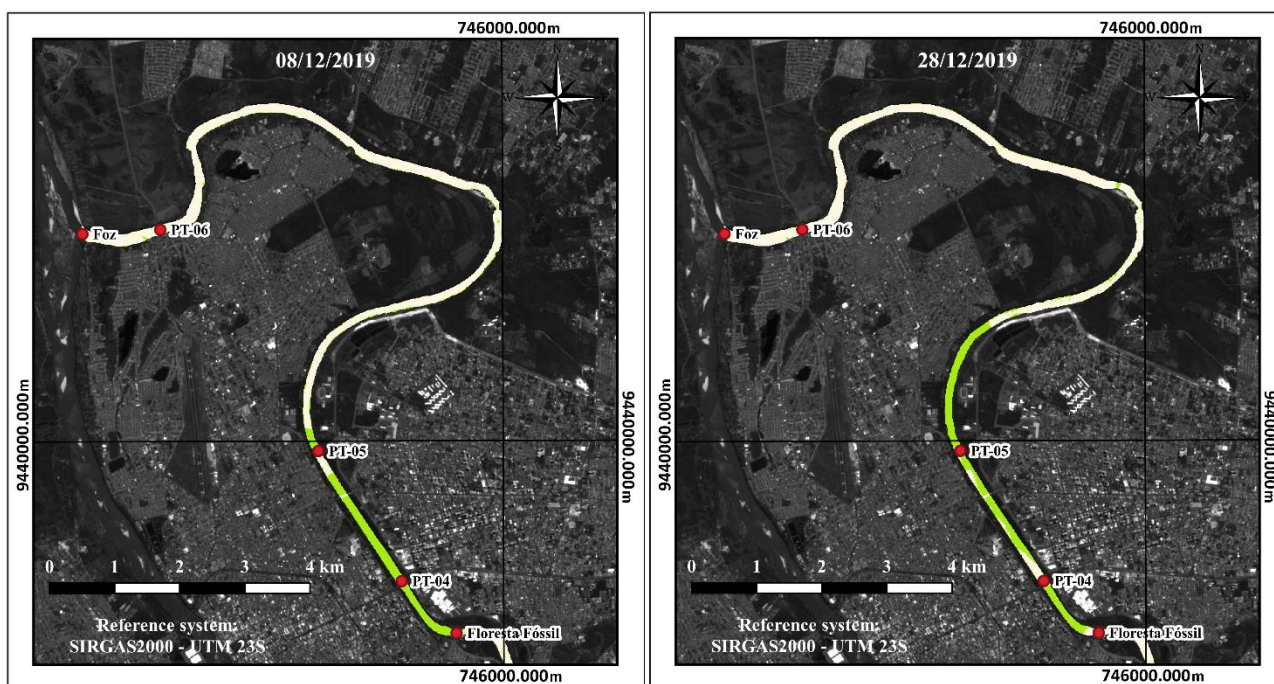


Figure 8. Spatial distribution of aquatic plant proliferation in November and December 2019.

In Figure 9, the areas covered by aquatic plants have increased successively in the dry months, presenting the following values: 6,847.5 m²; 65,371.3 m²; 168,736.4 m²; 386,193.9 m²; 430,608.5 m²; and 570,145.6 m². With the figure in mind, it can be seen that the monthly expansion rate peaked on October 14, 2019.

These results are in line with studies evaluating the water quality of the Poti River, which show this stretch as suitable for the growth of water hyacinths, as this place is the most urbanized, with the presence of several points of emission of effluents, solid residues and, probably, clandestine connections of domestic and industrial effluents in the rainwater drainage network (Mendes-Câmara, 2011; Oliveira e Silva, 2014; Oliveira Filho and Lima Neto, 2018). In addition, Bareuther et al. (2020) and Worqlul et al. (2020) reported that a strong linear correlation between the nutrient loads, water level, turbidity, and water and air temperatures and water hyacinth expansion was found. The use of Sentinel-2 data and GIS applications showed good results in mapping the spatial distribution of water hyacinth in lakes (Bareuther et al. 2020; Dersseh et al., 2020).

About the assessment of fresh biomass of water hyacinths in situ, at the end of the dry period, a ratio of 281.0 kg in 25 m² was obtained, reaching a value of 11.2 kg / m², with an average height individual plant of 0.5 m. Therefore, considering that the maximum area covered by water hyacinths at the end of December was 57 hectares, an estimated production of 6,408.4 tonnes of fresh biomass of water hyacinths. Generally, the proliferation of aquatic plants is due to several factors, including the increase in nutritional availability and the level of eutrophication, at high average temperatures and intense light radiation, at low wind speed, the damming of the waters of the Poti River by the Parnaíba River, the reduction in the flow, width and depth of the Poti River, as well as the lack of predators and competition between coexisting species, in addition to the Teresina City Hall not making investments in the mechanical removal of water hyacinths, as occurred in the period of 2016 to 2018 (Thomaz and Bini, 2003; Esteves, 2011; Lima and Augustin, 2014; Nunes et al., 2017; Teresina, 2017; Teresina, 2019). The covered areas disappear with the beginning of the rainy season, with an increase in the flow of the river.

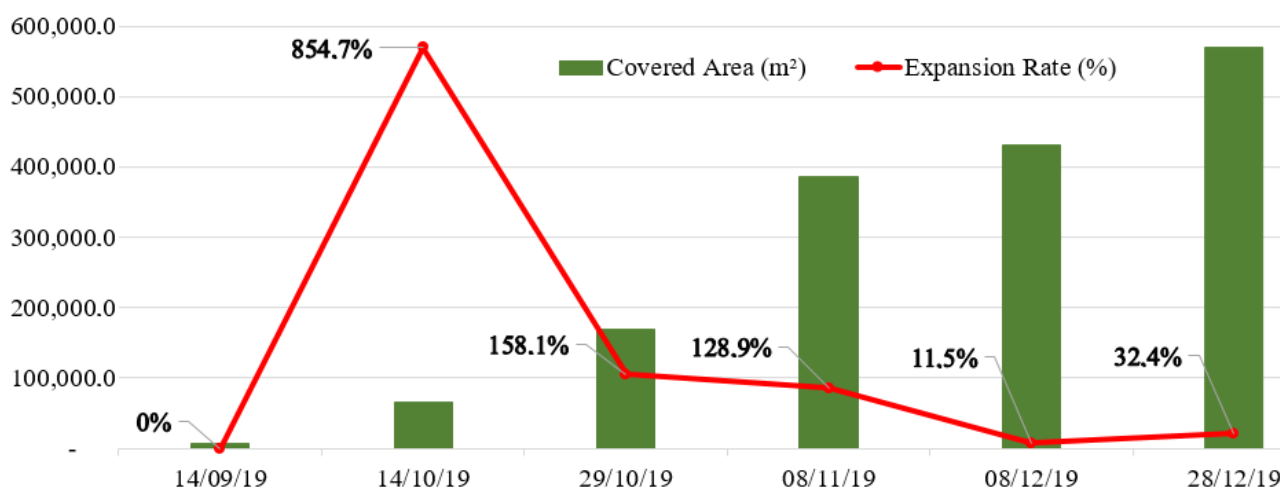


Figure 9. Graphical presentation of the covered area and expansion rate of water hyacinths.

Conclusions

In this study, the use of data from the Sentinel-2, A and B satellites in the remote sensing of urban rivers, in the Northeast region of Brazil, was evaluated. Considering a moderate correlation between the results of the quantitative punctual agreement between the data in situ and the values obtained with each semi-empirical algorithm, the NDCI index obtained better punctual performance than the MCI and MPH indices. This study confirms that the relationship between the B04 and B05 bands is the most suitable for the recovery of chlorophyll-a in that river, after the calibration of the indices to the water components of the Poti river, which is concurrent with observations made by Pereira et al. (2020).

The TSI, in 2016 and 2017, points to the predominance of the ultraoligotrophic class (73.2%), which is the lowest level of eutrophication, as well as showing variations in the oligotrophic (21.4%) and mesotrophic (5.4%) classes. All chlorophyll-a and phosphorus samples met the Class 2 limits for fresh water, established by CONAMA Resolution No. 357/2005. In addition, the results showed that the NDVI index, semiempirical, proved to be efficient for the detection and mapping of the proliferation of aquatic plants in the Poti River, clearly showing the location of the areas covered by water hyacinths. At the beginning of proliferation, a maximum expansion rate of 854.7% was assessed. At the end of the dry period, there was a peak of the area covered by the green carpet of 570,145.6 m² and a production of 6,408.4 tons of fresh biomass of water hyacinths.

The spatiotemporal distribution of chlorophyll-a and aquatic plants in the Sentinel-2A image maps is consistent with the pattern of occurrence determined by in situ data. In addition, the scale of representation of the maps is sufficient

for the management of these areas, due to the excellent spatial resolutions, of 10 m, and temporal, of five days. Therefore, the MSI sensor proved to be an adequate tool for the detection and mapping of chlorophyll-a concentrations and proliferation of aquatic plants in the Poti River.

The correct dimensioning and management of eutrophication and proliferation of aquatic plants are of great importance for the mobilization of institutions responsible for helping these regions, as it allows the anticipation of preventive and structured actions, guaranteeing a leap in quality in the provision of their services.

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