Chlorophyll-a Concentration in the Salto Grande Reservoir (Americana, Brazil) Estimated by Satellite Images

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Abstract

Humankind has a deep relationship with water, which is essential for life, since it is used to meet different human needs; however, human interactions and activities have degraded the quality of water bodies. In this context, monitoring water bodies becomes an essential tool to understand their spatial and temporal variability, as well as to help in decision-making and water resource management. Traditional monitoring, based on sample collection and laboratory analysis, can be considered a costly, one-off process that fails to present the characteristics of the entire water body. Remote sensing techniques can be used complementarily to traditional monitoring, allowing to observe the entire water body while presenting lower costs and short execution time. This study used remote sensing techniques to evaluate the trophic state of the Salto Grande reservoir using Chlorophyll-a (Chl-a) concentration as an analysis parameter. Located in the municipality of Americana, São Paulo, Brazil, the Salto Grande reservoir is situated on the Atibaia River, near its mouth, amidst a highly industrialized region with expressive monoculture. This reservoir has a history of degradation over time. Chl-a was estimated based on images from the MSI sensor present on the Sentinel-2 satellite, which underwent atmospheric correction by Sen2Cor software. Four algorithms using spectral band ratios were tested, with both linear and nonlinear adjustments. The values obtained were compared with data from analyses performed by CETESB, with close dates, at the study site and available to the public. The adjusted algorithms presented a correlation above 0.8, while the best adjustments for each algorithm showed a correlation greater than 0.9 and an error rate below 10% and 8 µg/L. Mishra and Mishra’s (2012) NDCI algorithm had the best applicability as it returned only positive values, in contrast to some algorithms, which returned negative Chl-a values. With the resulting values from the selected algorithm, the modified Carlson Trophic State Index was applied, and a high eutrophication index was observed in the reservoir.

1. Introduction

Water, especially surface water, is of paramount importance for biodiversity, as it plays a key role in biogeochemical cycles and is essential for food and energy production (TYLER et al., 2016).

Brazil holds a privileged position in terms of water resources, having almost 12% of the freshwater available on the planet; but this resource is not equally distributed throughout the country, being mostly concentrated in sparsely populated regions (NOVO, 2019; ANA, 2020).

The quality of this resource is a factor to be considered, since many water bodies have been affected by anthropic interference, which can reduce water quality and decrease biodiversity, in turn destabilizing ecosystem services and functions (DALU et al., 2015).

The risks to water resources are directly related to land use. Urban and agricultural areas are responsible for the greatest degradation—the first due to the lack of sanitation, adequate waste collection and sewage treatment, which leads to the deposition of untreated waste and effluents into the water body; and the
second due to the use of fertilizers and increased sediment transport to water bodies (CRUZ et al., 2019; MELLO et al., 2020).

Adding nutrients, such as phosphorus and nitrogen, to an aquatic system can cause various changes in its functioning and result in eutrophication (ESTEVES, 2011). Nutrient enrichment interferes with the development of certain communities, and increases the proliferation of harmful algae and consequent release of toxins into the water by these individuals (WATANABE et al, 2019), harming the biodiversity of the environment.

Due mainly due to the country’s energy matrix, predominantly hydroelectric, Brazilian waters are characterized by a large number of artificial reservoirs, whose volume vary depending on economic or climatic factors (NOVO, 2019).

In reservoirs, the eutrophication process worsens, because the increase in phosphorus and nitrogen combined with the longer retention time creates optimal conditions for cyanobacteria, a phytoplankton group known for its toxicity (WATANABE et al., 2019).

To assist in hydric resource and decision-making, as to minimize anthropic impacts related to watercourse, we must know their characteristics over time. Due to the differences in each region, location, access and availability of resources, however, the information available on the quality of these resources is unequal and even scarce.

Water quality is evaluated by measurements made on collected samples, which allows quantifying its physical, chemical or biological properties at a given location and instant of time (NOVO, 2019).

Although measurements taken in situ by traditional sampling methods and analyses are more accurate and widespread than those acquired indirectly, such as by remote sensing (GAIDA et al., 2020), these are costly and time-consuming approaches with limited spatial representativeness, which becomes a limiting factor for evaluating the quality of water resources (JUNIOR et al., 2019; BUMA AND LEE, 2021).

Spatial-temporal variations of water parameters are fundamental for its management, and such analyses can be made possible by methodologies developed with remote sensing techniques (GHOLIZADEH, MELESSE, REDDI, 2016). Remote sensing approaches enable a better understanding of physical and chemical changes in water bodies, facilitating the identification of possible disturbances in water bodies (SENT et al., 2021).

Of the water quality parameters that can be studied by remote sensing, Chlorophyll-a (Chl-a) stands out, a pigment present in photosynthetic organisms, such as phytoplankton organisms, which includes hundreds of microalgae and cyanobacteria species, largely responsible for the apparent color of the water and generally found in aquatic ecosystems like lakes and reservoirs (BARBOSA, 2019; RADIN, SÒRIA-PERPINYÀ, DELEGIDO, 2020).
Due to its correlation with trophic state, clarity and algal biomass of waters (MATSUSHITA et al., 2015), Chl-a is an important parameter to assess aquatic environments, as it represents a biological response to the increase in nutrient concentrations and the production of algae and cyanobacteria, known eutrophication agents (GHOLIZADEH, MELESSE and REDDI, 2016).

High Chl-a concentrations indicate changes in trophic state and are associated with reduced water quality and low biodiversity, which destabilizes ecosystem services and functions (DALU et al., 2015).

Understanding the dynamics of Chl-a concentrations is fundamental for the choice of adequate management, which can help restore ecosystem functions and services. Hence, frequent monitoring becomes essential for understanding such dynamics (DALU et al., 2015; LINS et al., 2019).

Thus, this study aimed to evaluate the trophic state of the Salto Grande Reservoir, Chl-a concentrations as a parameter analysis, estimated based on satellite images and data collected in situ by the environmental monitoring agency of the State of São Paulo, CETESB.

2. Materials And Methods

2.1. Study Site

Located in the municipality of Americana, eastern region of the state of São Paulo, the Salto Grande Reservoir has an area of 11.5 km² (MARTINS et al., 2011) and is part of the American Hydroelectric Power Plant, belonging to the Companhia Paulista de Força e Luz (CPFL).

The region (Fig. 1) is predominantly characterized by urban mesh and monoculture of sugar cane, citrus and pastures (NETO, 2013). The reservoir has been presenting a situation of degradation over time, with a high eutrophication rate, which has been worrying both the authorities and the population.

The increasing anthropic activity throughout the Atibaia basin has interfered with the nutrient concentrations in the reservoir, due to the large discharge of industrial and domestic effluents, and the surface runoff of agricultural inputs by rainwater (MARTINS et al., 2011).

When studying phosphorus accumulation in reservoir sediments, Missailidis et al. (2018) observed a progressive eutrophication process, indicating that the reservoir has been suffering from polluted water inputs for decades, which has been intensifying with population growth, besides contributions from soil leaching around the reservoir, related to fertilizer use.

Between the 1970s and 1980s, the reservoir saw an increase in tourism-related activities, which resulted in an increase of civil construction on its banks and, consequently, in domestic effluents disposal (MARTINS et al., 2011).

According to the regulating body Companhia Ambiental do Estado de Sao Paulo CETESB (2020), the reservoir is organically enriched, with high phosphorus concentrations in the sediments.
2.2. Field Data

CETESB monitors several water bodies in the state of São Paulo, and makes the results of the analyses and other data from the monitoring points available to the public through the CETESB InfoÁgua information system, and through annual water quality reports.

CETESB has a monitoring point in the central body of the reservoir (Fig. 2), located in front of the Yacht Club, named ATSG 02800. The Chl-a concentrations used in this study were obtained from the CETESB InfoÁguas, platform (https://sistemainfoaguas.cetesb.sp.gov.br/).

Monitoring in this sampling point started in 2017, with approximately four analyses performed yearly. Due to the SARS-CoV-2 (coronavirus) pandemic, however, CETESB performed only two samplings in 2020, and the situation normalized in 2021.

2.3. Image Acquisition and Atmospheric Correction

Chl-a concentrations in the reservoir were estimated by means of algorithms adjusted with Sentinel-2 satellite images, whose results were compared with in situ data made available by CETESB. We selected images with dates close to that of the CETESB samplings, using as a basis three days before and after, and showing less interference from clouds, over or near the study area (Table 1).

The Sentinel-2 satellite images were obtained from the United States Geological Survey (USGS) Earth Exploration database, with a spatial resolution of 20 m. This mission consists of the twin satellites Sentinel 2A and 2B, equipped with an MSI (MultiSpectral Imager) instrument. Images are provided as Level-1C product, that is, the radiometric measurements per pixel are in top-of-atmosphere (TOA) reflectance, with UTM/WGS84 projection (ESA, 2020).

The selected images underwent atmospheric correction by Sen2Cor algorithm, available in SNAP software (Sentinel Application Platform), in its default setting. When performing the atmospheric correction, the software converts the Level-1C images and delivers them as Level-2A products, which provide bottom-of-atmosphere (BOA) reflectance, called Surface Reflectance.

Surface reflectance was divided by π to convert the data into Remote Sensing Reflectance (Rrs), the input data used in the chosen algorithms.
Table 1
CETESB sampling data and respective imaging dates.

<table>
<thead>
<tr>
<th>Sampling date (dd/mm/yy)</th>
<th>Time</th>
<th>Chlorophyll-α (µg/L)</th>
<th>Rainfall in the last 24 hours</th>
<th>Sentinel-2 images date (dd/mm/yy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22/02/2018</td>
<td>12:58</td>
<td>20.58</td>
<td>Yes</td>
<td>24/02/18</td>
</tr>
<tr>
<td>16/08/2018</td>
<td>16:28</td>
<td>27.00</td>
<td>No</td>
<td>18/08/18</td>
</tr>
<tr>
<td>06/12/2018</td>
<td>12:02</td>
<td>12.43</td>
<td>No</td>
<td>06/12/18</td>
</tr>
<tr>
<td>21/02/2019</td>
<td>13:25</td>
<td>27.45</td>
<td>Yes</td>
<td>24/02/19</td>
</tr>
<tr>
<td>26/06/2019</td>
<td>12:44</td>
<td>11.49</td>
<td>No</td>
<td>24/06/19</td>
</tr>
<tr>
<td>29/08/2019</td>
<td>11:51</td>
<td>123.63</td>
<td>No</td>
<td>28/08/19</td>
</tr>
<tr>
<td>12/02/2020</td>
<td>11:17</td>
<td>33.86</td>
<td>Yes</td>
<td>14/02/20</td>
</tr>
<tr>
<td>08/02/2021</td>
<td>10:34</td>
<td>36.98</td>
<td>No</td>
<td>08/02/21</td>
</tr>
</tbody>
</table>

### 2.4. Chlorophyll-α concentration Estimation

Chlorophyll-α (Chl-α) concentration was estimated by four algorithms, proposed by other authors, that use spectral band ratios, using as input water spectral reflectance in remote sensing (Rrs (λi)).

The two- and three-band algorithms proposed by Dall’Olmo and Gitelson (2005), the NDCI algorithm, proposed by Mishra and Mishra (2012), and the SLOPE algorithm proposed by Mishra and Mishra (2010) were applied. For identification purposes, the algorithms were referred to as DG2B, DG3B, NDCI and SLOPE, respectively.

DG3B was originally developed to estimate pigment content in terrestrial vegetation, but Dall’Olmo and Gitelson (2005) observed that it could be used to assess Chl-α concentration (Cchl-α) in complex waters.

\[
Cchl-\alpha \propto \left[ R_{rs}^{-1}(\lambda_1) - R_{rs}^{-1}(\lambda_2) \right] \times R_{rs}(\lambda_3) \quad (1)
\]

As an alternative to the three-band model, Dall’Olmo and Gitelson (2005) proposed a two-band model (DG2B), which uses the ratio between red and NIR (near infrared) bands.

\[
Cchl-\alpha \propto \frac{R_{rs}(\lambda_2)}{R_{rs}(\lambda_1)} \quad (2)
\]

NDCI (Normalized Difference Chlorophyll Index) is an algorithm proposed by Mishra and Mishra (2012) that also uses red and NIR bands to avoid CDOM and TSS influence on the water reflectance spectra at shorter wavelengths.

\[
Cchl-\alpha \propto \frac{[R_{rs}(\lambda_2) - R_{rs}(\lambda_1)]}{[R_{rs}(\lambda_2) + R_{rs}(\lambda_1)]} \quad (3)
\]

Another algorithm tested, called SLOPE, proposed by Mishra and Mishra (2010), uses bands with scattering sensitivity and higher Chl-α absorption.
Cchl-a ∝ [R rs (λ2) - R rs (λ1)] / (λ2 - λ1) (4)

We used the remote sensing reflectance of bands referring to wavelengths near 700 nm and 670 nm, as Rrs (λ2) and Rrs (λ1). These wavelengths have been widely used to estimate Chl-a concentrations, because the reflectance peaks in these regions are the most sensitive to variations in Chl-a concentrations in water and to the highest Chl-a pigment absorption, respectively (MATTHEWS, 2011; MISHRA AND MISHRA, 2012).

Moreover, the DG3B algorithm uses a third wavelength, near 750 nm (Rrs (λ3)), as its reflectance values are less affected by absorption (GITELSON et al, 2008).

Considering the algorithms and respective wavelengths proposed by the authors and comparing these values with the MSI imaged bands, the images corresponding to Bands 4 (Red), 5 (Red Edge) and 6 (Red Edge) were used as Rrs (λ1), Rrs (λ2) and Rrs (λ3), respectively.

After applying all algorithms on the images, the pixel values were compiled with the corresponding coordinates of the CETESB sampling point and surrounding pixels, forming a 3x3 grid, totaling 9 pixels. Next, the mean of these values was calculated.

The calculated mean values of each algorithm were compared to the CETESB values by regression models, using the following statistical parameters: correlation coefficient (R²), root mean squared error (RMSE), normalized root mean squared error (NRMSE), mean absolute percentage error (MAPE) and Bias. The function (f (x)) with the highest correlation (R² > 0.8) and lowest percentage error values was chosen and applied to all images in the reservoir area.

To avoid errors in the interpretation of results, we eliminated the areas with cloud cover or macrophyte cover by creating a mask with the delimitation of these areas and later removing them from the total area of the reservoir.

3. Results And Discussion

3.1. Field Collected Chl-a Data

Considering the sample analysis results obtained by CETESB regarding Chl-a at the sampling point in Salto Grande Reservoir (Fig. 3), we observe a variation of Chl-a concentrations, which ranged from 10 µg/L to 130 µg/L in the historical series analyzed.

In 2017, Chl-a concentration reached its highest values, with results higher than 60 µg/L, while the following period, from 2018 to the first semester of 2019, showed lower Chl-a values.

The months of June and August 2019 registered the greatest differences in Chl-a concentration, from 11.49 µg/L, the lowest value sampled, in June to 123.63 µg/L in August. This period coincides with the
winter school vacations in July, which may have influenced the number of residents or frequenters of summer houses located near the reservoir.

Quantitative and qualitative water variations depend on the type of ecosystem (ZAKEYUDDIN et al, 2016), the dynamics of aquatic systems, and the concentrations and interactions between their components, such as Chl-a concentrations, which are influenced by biotic and abiotic factors.

A natural abiotic factor influencing Chl-a concentrations is rainfall. Periodic precipitation can lead to concentration or dilution of dissolved nutrients and particulates in the aquatic system (BOUVY et al, 2003).

We also compiled the remote sensing reflectances (Rrs) of the eight selected images, at the CETESB sampling point (Fig. 4), at different wavelengths, according to the images of the spectral bands obtained by the Sentinel-2 MSI sensor.

Figure 4 points to the presence of Chl-a, such as high absorption in the blue and red regions, high reflectance in the green region (550 nm), and especially the reflectance peak in the region near 700 nm.

But some of these peaks are influenced by other water components, such as the region near 560 nm, where contributions from CDOM and suspended solids can occur, and in the region near 700 nm, where we observe the influence of suspended solids. (SANTOS et al., 2019).

The spectrum for 28/08/2019 shows well-defined peaks, corresponding to Chl-a, in the visible region and an increase in reflectance starting at 700 nm, and is the only spectrum to present higher reflectances in this wavelength than in the visible region. These peaks suggest high suspended solids content and high phytoplankton biomass.

To verify the presence of suspended solids in the reservoir, we compiled turbidity, total dissolved solids, and total solids data available at the InfoÁguas platform (Table 2), on the dates corresponding to the images. We calculated the suspended solids values by subtracting the total dissolved solids from the total solid’s values.

Results show that the sampling date 29/08/2019, whose corresponding image was taken in 28/08/2019, presents not only the highest Chl-a index, but also the highest suspended solids content, as well as the highest turbidity, of all the samples. Turbidity is directly proportional to the presence of suspended solids, since it measures the difficulty for a beam of light to pass through water due to the presence of suspended solid matter.
Table 2
Content of total dissolved solids, total solids, turbidity, Chl-a, and suspended solids at the sampling point.

<table>
<thead>
<tr>
<th>Sampling date (dd/mm/yy)</th>
<th>Imaging date (dd/mm/yy)</th>
<th>Chl-a (µg/L)</th>
<th>Total Dissolved Solids (mg/L)</th>
<th>Total Solids (mg/L)</th>
<th>Suspended Solids (mg/L)</th>
<th>Turbidity (UNT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22/02/18</td>
<td>24/02/18</td>
<td>20.58</td>
<td>128</td>
<td>132</td>
<td>4</td>
<td>6.6</td>
</tr>
<tr>
<td>07/06/18</td>
<td>09/06/18</td>
<td>43.44</td>
<td>208</td>
<td>218</td>
<td>10</td>
<td>5.7</td>
</tr>
<tr>
<td>16/08/18</td>
<td>18/08/18</td>
<td>27.00</td>
<td>196</td>
<td>202</td>
<td>6</td>
<td>4.5</td>
</tr>
<tr>
<td>06/12/18</td>
<td>06/12/18</td>
<td>12.43</td>
<td>126</td>
<td>128</td>
<td>2</td>
<td>15.00</td>
</tr>
<tr>
<td>21/02/19</td>
<td>24/02/19</td>
<td>27.45</td>
<td>148</td>
<td>162</td>
<td>14</td>
<td>4.34</td>
</tr>
<tr>
<td>26/06/19</td>
<td>24/06/19</td>
<td>11.49</td>
<td>148</td>
<td>164</td>
<td>16</td>
<td>2.33</td>
</tr>
<tr>
<td>29/08/19</td>
<td>28/08/19</td>
<td>123.63</td>
<td>188</td>
<td>208</td>
<td>20</td>
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<tr>
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<td>14/02/20</td>
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<td>184</td>
<td>192</td>
<td>8</td>
<td>11.2</td>
</tr>
<tr>
<td>08/02/21</td>
<td>08/02/21</td>
<td>36.98</td>
<td>100</td>
<td>112</td>
<td>12</td>
<td>9.54</td>
</tr>
</tbody>
</table>

3.2. Application of algorithms

By applying the algorithms and adjusting several linear and nonlinear trend lines, we verified the degree of correlation ($R^2$) between the algorithm-estimated values and the CETESB data. Figure 5 shows the regressions that showed the highest correlation with the lowest error rates for each algorithm.

Most points are concentrated in a range from 20 to 40 mg/m³, with one high Chl-a point above 120 mg/m³ and two points below 20 mg/m³. In all algorithms, the 2nd degree polynomial and linear regression trend lines showed the highest correlations.

In the DG2B algorithm, the linear and second-degree polynomial regressions showed similar correlation and error values, however, we chose the linear regression as the most indicated because it presented the lowest MAPE value and the lowest bias.

The SLOPE algorithm had the highest correlation value and the lowest errors, except for the MAPE values, which present the lowest error with NDCI linear regression.

The remaining algorithms showed similar values, with a 0.95 correlation, RMSE around 7 mg/m³, NRMSE at 6%, and MAPE ranging from 9 to 11%. DG2B can be considered the second-best algorithm, showing the best RMSE and NRMSE correlation values, followed by NDCI and, finally, DG3B, with the highest error values and lowest correlation value.

Some authors have obtained similar results, such as Neil et al. (2019), who evaluated the performance of 48 different Chl-a estimation algorithms based on data collected from 185 continental and coastal
aquatic systems, which covered 13 optically different water types. Of these, four algorithms stood out as most suitable and accurate, including DG2B and NDCI.

When studying the Ibitinga Reservoir, also in São Paulo, Cairo et al. (2020) classified the Chl-a concentrations in ranges and tested several algorithms for each band, pointing to the SLOPE algorithm as the most suitable for waters with Chl-a concentrations between 19.51 and 87.63 mg/m³, corroborating our study.

However, when adjusted for the 2nd degree polynomial and linear regressions, the SLOPE returned negative values. The DG2B algorithm showed similar results when adjusted for the 2nd degree polynomial regression.

Watanabe et al. (2019), when investigating the trophic gradient of three cascading reservoirs on the Tietê River, in São Paulo, described a similar scenario, which led the authors to choose an algorithm presenting positive values, the NDCI algorithm with linear adjustment, even though they presented less favorable correlation and error values.

Thus, we used the NDCI algorithm, because although it presented the third best result, it did not return negative Chl-a concentration values. According to Mishra and Mishra (2012), NDCI has the advantage of varying between −1 and +1, so that qualitative Chl-a mapping and bloom detection using remote sensing is possible even for remote areas where field data are unavailable or unusable.

Despite the correlation indexes obtained in this study, even higher than those obtained by other authors, the present study sought to use data already available to the public, without collecting new data, which resulted in a reduced number when compared to other authors.

Due to the reduced number of data, some Chl-a concentration ranges were not considered, which can cause errors in the estimate. As the water body has only one monitoring point, the water characteristics at this point are understood to be the same for the entire reservoir area—a wrong assumption given the trophic state along the reservoir.

We suggest, therefore, collection of new data for more accurate results regarding different situations.

### 3.3. Spatio-temporal Chl-a distribution

We applied the NDCI algorithm adjusted for the 2nd degree polynomial function to all images, which resulted in Chl-a concentration values in mg/m³ (Fig. 6). Chl-a concentrations ranged from values lower than 25 mg/m³ up to 150 mg/m³, reaching 152.3 mg/m³, with the lowest value being 8.80 mg/m³.

Overall, the lowest concentrations are found closer to other watercourses. Chl-a concentrations tend to increase throughout the reservoir, with the highest concentrations found in areas closest to the dam and banks.
Areas with cloud cover and macrophyte interference were removed and represented by masks. Although these plants interfere in the results, with data showing its reflectance rather than the reflectance of the water, the presence of this vegetation indicates an environment with enriched concentrations of nutrients, which influence its growth.

On 24/02/2019 and 24/06/2019, we can also note the presence of macrophytes near the sampling point. On 28/08/2019, the concentration of Chl-a is relatively high on the reservoir banks, especially near the CETESB sampling point.

This location is mainly occupied by houses and also hosts the Yacht Club. The circulation and occupancy rate at the site can lead to an increase in domestic sewage or waste, which influence the amount of nutrients and the eutrophication process in this area.

An objective instrument used to compare the eutrophication state of aquatic systems is the Trophic State Index (TSI) (NOVO et al., 2013). In our study, TSI was verified using the Chl-a concentration values (Fig. 7) obtained from the Modified Carlson Index, the same as used by CETESB, an instrument based on three indicators: Secchi depth, total phosphorus and Chl-a.

The TSI consists of six categories classified according to Chlorophyll-a as follows: ultra-oligotrophic (Chl-a ≤ 1.17 mg/m³), oligotrophic (1.17 < Chl-a ≤ 3.24 mg/m³), mesotrophic (3.24 < Chl-a ≤ 11.03 mg/m³), eutrophic (11.03 < Chl-a ≤ 30.55 mg/m³), supereutrophic (30.55 < Chl-a ≤ 69.05 mg/m³) and hypereutrophic (Chl-a ≥ 69.05 mg/m³).

Disregarding areas covered by clouds or macrophytes, most of the reservoir area can be classified as eutrophic or above. According to the lowest estimated value, 8.8 mg/m³, the lowest TSI classification obtained in the reservoir was mesotrophic.

Of lower incidence, the mesotrophic category occupies 0.41% of the area, with no areas classified in this category on 02/24/2018 and 08/28/2019, whereas the eutrophic category, which occupies 63% of the area, shows the highest incidence.

Hypereutrophic areas are usually located near the reservoir's dam and banks. On 08/28/2019, we can observe the largest area classified as hypereutrophic, with the remaining area classified as supereutrophic.

Although we did not use data collected from the region closest to the dam, due to the presence of macrophytes, this site can have high rates of nutrients and consequently high eutrophication rates, due to the retention of nutrients and other compounds near this location.

On 06/24/2019, the reservoir source is supereutrophic, becoming eutrophic in the second region, contrasting with the other images, in which the second region is shown to have higher Chl-a concentration. Figure 8 illustrates the percentage of area occupied by each category.
On all analyzed dates, most of the reservoir is classified as hypereutrophic or above. On 02/24/2019 and 06/24/2019, most of the area is classified as supereutrophic. On 06/24/2019, 88% of the area can be classified as eutrophic.

Interestingly, the image from 08/28/2019 shows large hypereutrophic and supereutrophic areas, corresponding to approximately 58% and 41.9% of the total area, respectively, leaving only 0.1% classified as eutrophic.

All these analyses unveil the worrying situation of this reservoir. The high eutrophication rate found can interfere with the biogeochemical cycle of this environment and damage the local biodiversity, the neighborhood, as well as the population who have contact with the water or consume some organism from this environment.

4. Conclusions

Based on the MSI images, obtained from the Sentinel-2 satellites, we estimated Chl-a by means of algorithms. Importantly, these images showed key characteristics for their use in this study, such as high temporal resolution, larger number of bands and good spatial resolution.

The tested algorithms efficiently estimated Chl-a in the Salto Grande Reservoir, allowing to analyze their spatial and temporal distribution. The linear and 2nd degree adjustments showed the best results for all algorithms.

The NDCI algorithm proved to be more applicable and efficient to the study site, mainly for returning values between –1 and +1, making all estimated Chl-a values positive, discussed by the authors when proposing this method.

When adjusted by 2nd degree polynomial regression, this algorithm presented a correlation of 0.95, with error rates less than 10%. The error values returned were 7.36 mg/m³ and 6.6 and 9.4%.

Our findings clearly demonstrated the possibility of using satellite images for monitoring the Salto Grande Reservoir. However, further studies with new data collected in situ and new sampling points throughout the reservoir are needed, for the choice and better adjustment of the algorithms and to obtain more accurate results for different situations.

Regarding interferences in Chl-a estimation, our data showed macrophytes in the region, occupying a significant part of the site surface. But despite interfering in the results and applicability of the algorithms, their presence already suggests the trophic state of the water.

Based on the algorithms applied, the satellite images and the CETESB data, we conclude that the Salto Grande Reservoir is in a critical eutrophication situation.
To minimize this process, we indicate increased monitoring, inspection and application of sanitation policies, and water resource management. Study and application of environmental management techniques adequate to the environment can help minimize local pollution and environmental damage.

Declarations

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**Figures**

*Figure 1*

Location and land uses of the municipality of Americana, SP. Source: UGRHI PCJ Committee.
Figure 2

Location of CETESB's sampling points in the Salto Grande Reservoir.
Figure 3

Variation of Chl-a concentration in the Salto Grande Reservoir according to CETESB data.

Figure 4

Reflectance at CETESB's Sample Point

Figure 4
Reflectance of Sentinel-2 images at the CETESB sampling point.

Figure 5

Trend line, correlation and error data between actual and estimated values.
Figure 6

Chl-a concentrations estimated by NDCI algorithm.
Figure 7

TSI of Salto Grande Reservoir.
Figure 8

Percentage of area occupied by each TSI class in the Salto Grande Reservoir.