Remote sensing of cyanobacterias with Sentinel-2 in the Salto Grande

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Abstract

The Salto Grande Reservoir of the Uruguay River experiences recurrent increases of cyanobacteria bloom, which negatively impacts water quality, with adverse consequences for public health and tourism. This study uses images from the Sentinel-2 satellite to investigate different methods for detecting and monitoring cyanobacteria. Two indices are calculated and two models are applied for the detection of cyanobacteria: the Normalized Difference Vegetation Index (NDVI), the Normalized Difference Water Index (NDWI) and Chlorophyll-a models M1 and M2, which have not previously been evaluated with images from Sentinel-2. NDVI is commonly used to identify areas with vegetation cover. The NDWI, using green and near-infrared (NIR) bands, is used as a filter for the application of Chlorophyl-A models since it is very useful for the identification of aquatic areas. Both M1 and M2 estimate the concentration of chlorophyll in the water, with model M2 demonstrating greater efficiency in the detection of cyanobacteria compared to model M1. Sentinel-2 images allow the correct observation of variations in the concentration of cyanobacteria in the riverbed, facilitating the monitoring of seasonal changes and cyanobacteria blooms. The results of our investigation underlines the effectiveness of NDWI when used with the Sentinel-2 images for identifying surface water areas and the M2-Chlorophyll-a model for detecting cyanobacteria in them. Combining these indices with on-site measurements is likely to offer a robust approach to monitoring and managing of the Salto Grande Reservoir.

1. Introduction

The Salto Grande Reservoir, Figure 1, is an artificial lake, created by the construction of the Salto Grande Dam on the Uruguay River, which serves to feed a hydroelectric power plant shared by Argentina and Uruguay. It is situated in the central part of the Uruguay River basin, approximately 15 km north of the cities of Salto, Uruguay, and Concordia, Argentina. The lake is a popular spot for recreational activities as boating, fishing, and swimming. The surrounding areas offers beautiful landscapes and opportunities for outdoor activities as hiking and picnicking.

This Reservoir experiences recurrent increases of cyanobacteria blooms. The excessive growth of these microorganisms dyes the water with their blue-green color almost permanently (Bordet, 2019). Cyanobacteria cause significant alterations in water quality: affecting its pH, reducing dissolved oxygen levels, and introducing high toxicity through the production of cyanotoxins (Kruk et al., 2019; Bordet, 2019). These toxins, often from Microcystis aeruginosa, primarily affect the liver of the animals and can be harmful to fish, birds and mammals, in particular, humans (Butler et al., 2009). Cyanotoxins pose an important risk to public health, causing skin irritations, respiratory conditions, and gastrointestinal and liver disorders.

During the summer, cyanobacteria blooms become more prominent due to rising temperatures (Izaguirre et al., 2018; Bonilla et al., 2015). The problem is exacerbated by nutrient runoff from agricultural activities, particularly phosphorus and nitrogen (Federici et al., 2022; Aguilera et al., 2018; Goyenola et al., 2015). Excessive blooms affect beaches and recreational areasnear the reservoir and raise concerns among residents and tourists. Consequently, the attractiveness of public areas and tourist influx - a vital resource of the local and regional economies - are affected.

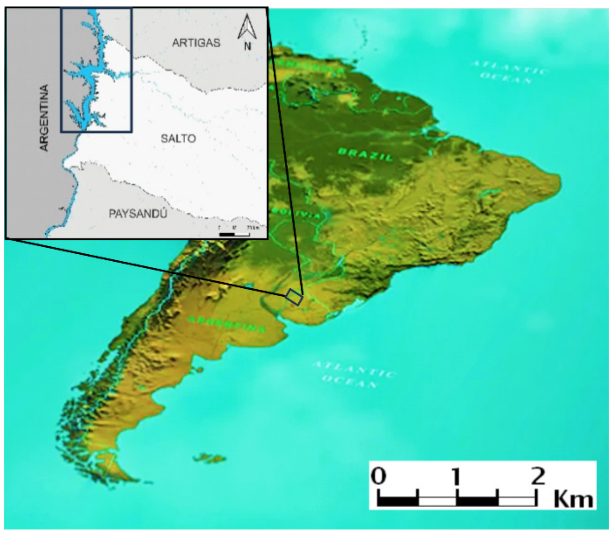

Figure 1. Location of the Salto Grande Reservoir.

Uruguayan River Matters, in collaboration with the Binational Commission that administers Salto Grande Dam, conducts the Monitoring and Trophic Status Program of the Uruguay River Beaches. This program ais aimed at analysing the spatial and temporal variations of the phytoplanktonic community, particularly cyanobacteria. (Izaguirre et al., 2018). Addressing this issue is crucial to protect public health and to preserve the regional tourism.

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Currently, the use of multispectral satellite imaging is essential for monitoring environmental phenomena due to the ability of this method to provide accurate data over vast areas of study. According to Berdugo Muñoz (2016), processing these images allows to estimate the spatial and temporal variation of water quality in a reservoir. Recent work has demonstrated the potential of satellite images for monitoring surface water quality (García Díaz, 2023; Carrasco Vela, 2019). In particular, Fournier et al. (2024) have shown the effectiveness of using satellite imagery for detecting cyanobacteria.

Satellite images can also be used to identify the dynamics of vegetation and water bodies (Veneros et al., 2020). A common processing technique for multispectral satellite images is the calculation of the Normalized Difference Vegetation Index (N DV I) (Rouse et al., 1973), which is used to assess vegetation health and density. Although it may not initially seem suitable for identifying cyanobacteria, it can act as an indicator of water surfaces. It is calculated using the visible red (RED) and near-infrared (NIR) spectrum bands as shown in equation 1.

$$NDVI = \frac{NIR-RED}{NIR+RED}, \tag{1}$$

NDVI values range from -1 to 1 (Gao, 1996). Values close to 1 indicate dense and healthy vegetation, while values close to -1 indicate the absence of vegetation or the presence of water bodies. Conversely, the Normalized Difference Water Index (NDWI) (McFeeters, 1996) is specifically used to delineate water contours and measure water content in vegetation. This indice is calculated using the visible green (GREEN) and NIR spectrum bands as shown in equation 2.

$$NDWI = \frac{GREEN-NIR}{GREEN+NIR}, \tag{2}$$

High NDWI values indicate the presence of water, while low values suggest dry surfaces or vegetation. This index is useful for filtering out areas without water in satellite images. The Chlorophyll-a (Cla) models are used to estimate the concentration of chlorophyll in bodies of water, which is associated with the presence of phytoplankton and, in many cases, cyanobacteria (Bonasea et al., 2014).

The objective of this study is to explore the capability of the NDV I and NDWI indexes and two Cla models, when used with Sentinel-2 satellite images to visualize and monitor cyanobacteria. The high spatial resolution of this type of images makes possible to appropriately calculate these quantities for detection.
The present study is focused on the Salto Grande Reservoir. The proposed methodology can be complemented with on-site measurements to enhance its effectiveness and provide a more comprehensive understanding of the analysed issue. The results of this investigation are particularly important for addressing high concentrations of cyanobacteria and then, to suggest specific interventions in this matter.

2. Methods

The study was conducted in a rectangular area that included the Salto Grande Reservoir and portions of the surrounding land, of the Uruguay and Argentina territories. This area was selected due to the year-round accumulation of cyanobacteria, evidenced by regular field observations. The study region is defined by the geographic coordinates shown in Table 1.

Boundary corner	Latitude	Longitude
1	−31.138962°	−58.07055°
2	−31.098519°	−58.07055°
3	−31.098519°	−58.007389°
4	−31.138962°	−58.007389°

Table 1. Coordinates of the polygon boundary corners

Figure 2 illustrates the specific location within the context of Salto Grande Lake in Salto, Uruguay.

To obtain the Sentinel 2 images, we primarily used the programming code developed by Facciolo (2019), which can be run in a Jupyter notebook and has been adapted and complemented for our purposes. The study period spanned approximately one year, from November 30, 2018, to November 20, 2019. In the area of interest, 72 Sentinel-2 satellite images were obtained. These images were filtered for the cloud cover, selecting only those with a maximum of 1% cloudiness. The result was 16 images corresponding to clear days. From the filtered images, the specific area of study of Table 1 was cropped, and the following bands were downloaded: Blue (B2): 490 nm, Green (B3): 560 nm, Red (B4): 665 nm, and Near Infrared (NIR, B8): 842 nm, all with a spatial resolution of 10 m (Pérez et al., 2020). The NDVI and NDWI were calculated using these bands and equations 1 and 2, whereas the Cl_a models were developed according to equations 3 and 4, evaluating the contribution of each to the detection of cyanobacteria.

The NDVI and NDWI indices were used as filters to detect vegetal cover and water surface, and then used in the calculation of Cl_a models. Two models proposed by Bonasea et al. (2014) were applied. The models M1 (equation 3) and M2 (equation 4), require the green and red bands.

$$Cl_a = -47.5 - 1.53\,.\,GREEN + 3.58\,.\,RED, \tag{3}$$

$$Cl_a = 77.24 - 5.30\,.\,GREEN + 6.58\,.\,RED, \tag{4}$$

In Bonasea et al. (2014), the results of these equations were derived using satellite images from the Enhanced Thematic Mapper Plus (ETM+) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensors, present on the Landsat 7 and TERRA satellites, respectively.

In our study, we utilized images from the Sentinel-2 satellite, an Earth observation mission developed by the European Space Agency (ESA) as part of the Copernicus program. Sentinel-2, comprising the Sentinel-2A and Sentinel-2B satellites, has been designed to monitor forest evolution, land surface changes, and natural disaster management (Pérez et al., 2020). This satellite provides multispectral data with 13 bands in the visible, NIR, and shortwave (SW) spectra, covering the globe from 56° S to 84° N. Images are captured every five days, with spatial resolutions of 10 m, 20 m, and 60 m, and a field of view of 290 km. An open data policy facilitates free access to this information.

Maps of the evaluated quantities were constructed, analyzed and compared to references. Finally, a time series of the Cl_a models for M1 and M2 was created to recognize the variation of cyanobacteria during the study period.

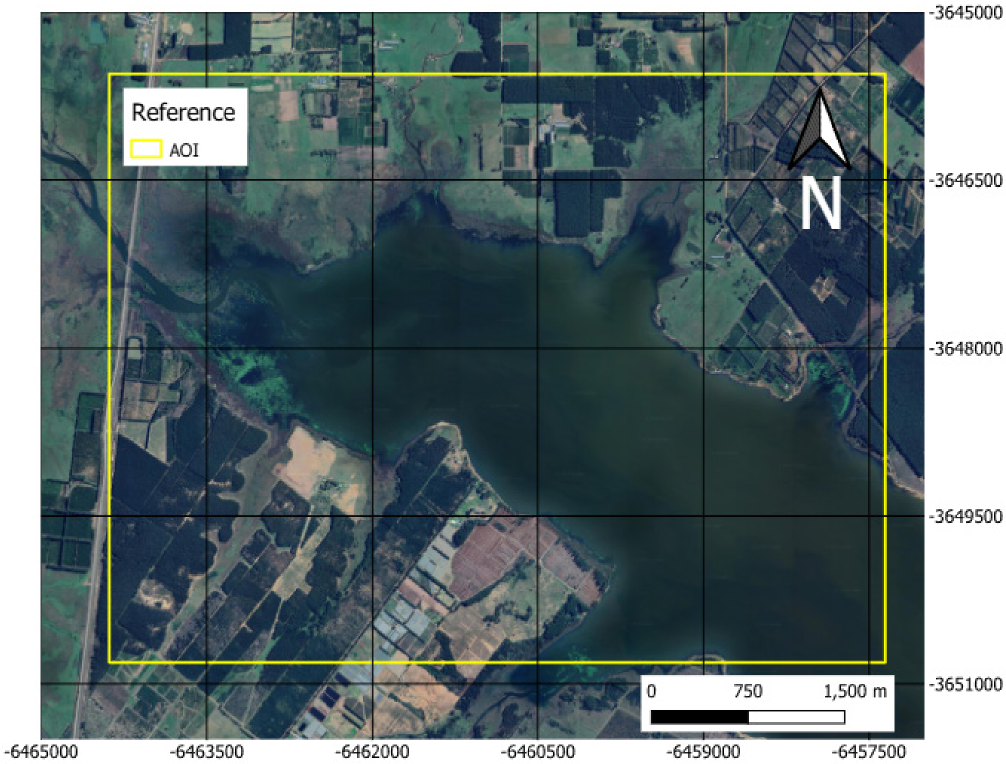


Figure 2. Study area in the Salto Grande Reservoir.

3. Results

N DV I and N DW I indices were calculated for the area of interest, and their visualizations shown on a scale from 0 to 1. Values close to 0 are represented in blue, while values close to 1 are shown in red. Figures 3 and 4 present the NDVI and NWDI results obtained for one day during the exceptional blooms observed in the summer of 2019 (Kruk et al., 2019). The date of the image is February 18, 2019, at 1:51 p.m.

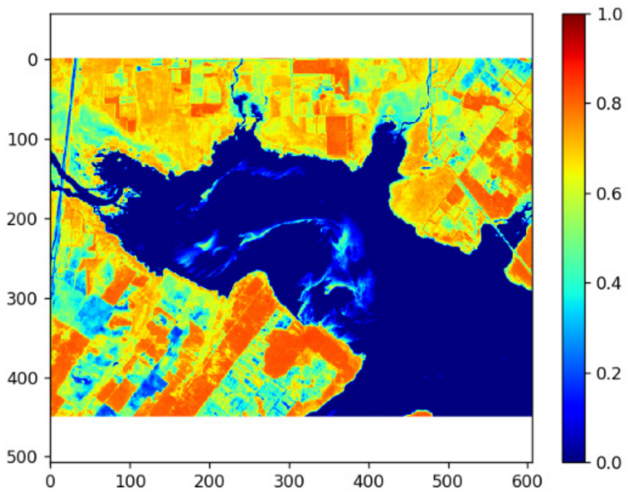


Figure 3. NDVI of the study area on February 18, 2019, at 1:51 p.m., both with a color scale ranging from 0 (blue) to 1 (red).

As expected, the NDVI does not clearly identify vegetation in the water zone. The water zone is roughly defined by values less than 0.5 of the indice. On the contrary, the NDWI is more specific for identifying areas with the presence of water. An NDWI greater than 0 is suitable for identifying the study area. From the time sequence of NDWI images, as those of Figure 5, it is evident that this index is potentially useful for studying changes in the river channel area during floods or droughts.

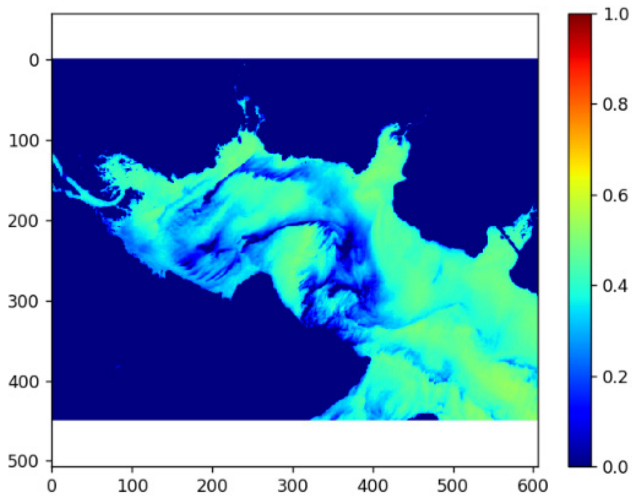
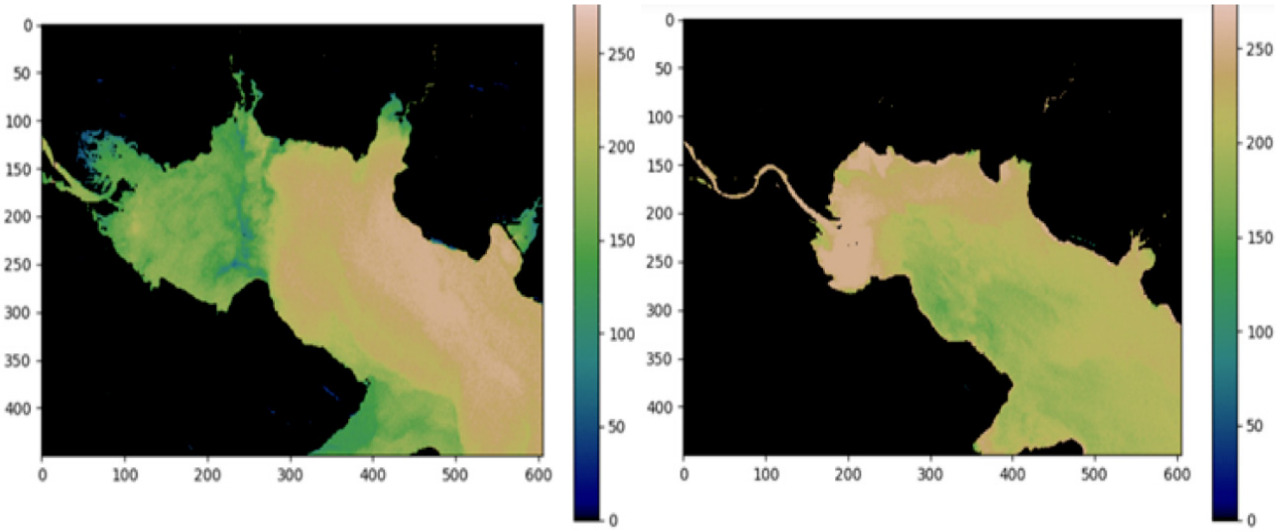
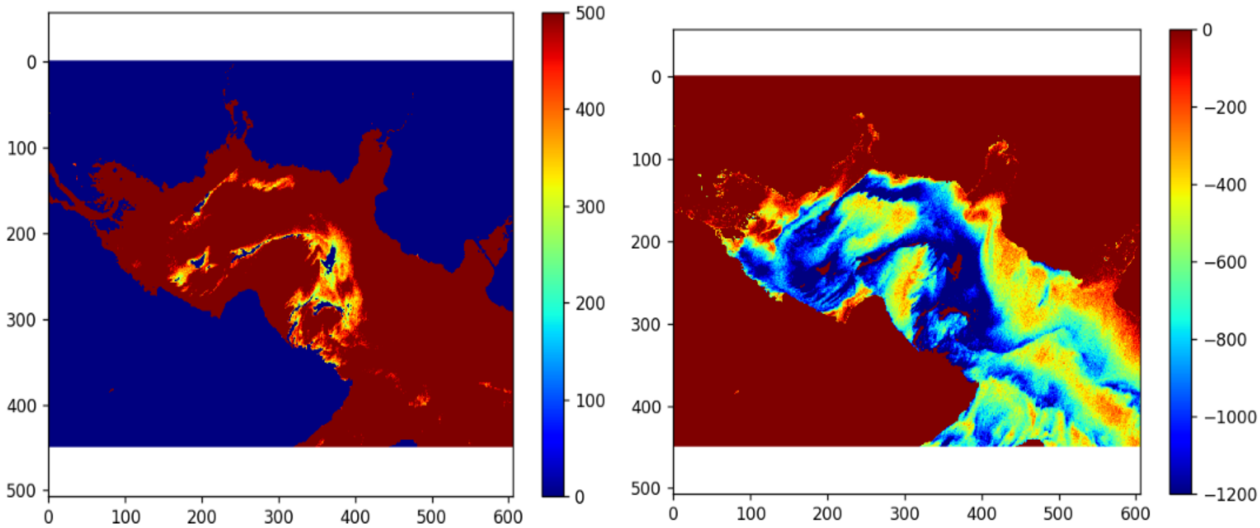


Figure 4. NDWI of the study area on February 18, 2019, at 1:51 p.m., both with a color scale ranging from 0 (blue) to 1 (red).



(a) Reservoir level of 34.82 m for May 25, 2019. (b) Reservoir level of 32.9 m for August 27, 2019.

Figure 5. Comparison of NDWI correspondent to two days with different reservoir levels: 34.82 m (left) and 32.9 m (right).



(a) Cl_a for M1 with a color scale ranging from 0 (blue) to 500 (red). (b) Cla for M2 with a color scale ranging from 0 (red) to -1200 (blue).

Figure 6. Chlorophyll-a M1 and M2 models, dated February 18,2019, at 1:51 p.m.

These figures show the variation in the river channel area between May 25, 2019, and August 27, 2019. The difference in levels can be contrasted with the Salto Grande Reservoir levels of 34.8 m and 32.9 m, respectively (Comisión Técnica Mixta de Salto Grande, 2019).

The NDWI > 0 criterion was used to filter areas that do not correspond to the watercourse. As the water level in the Salto Grande Reservoir rises, the flooded area increases. Figure 6 shows the Chlorophyll-a values of M1 and M2 for 18 February 2019, at 13:51 hours. It can be observed that M1 is less efficient in detecting cyanobacteria than M2.

Figure 7 shows the results provided by each model which can be compared with what is observed in the RGB image, Figure 8. This comparison shows that M2 is more appropriate for detecting cyanobacteria than M1.

4. Conclusion

This study makes use of Sentinel-2 satellite images to explore methods for detecting and monitoring cyanobacteria. This information is essential to properly evaluate responses to elevated concentrations of these organisms.

The NDVI and NDWI, were calculated to identify vegetation and the water zone and two Chlorophyll-a models (M1 and M2) were tested for cyanobacteria detection, which have not been previously evaluated with Sentinel-2 imagery.

The NDWI, utilizing green and NIR bands, excels at identifying aquatic areas and serves as a filter for the application of the Chlorophyll-a indexes. M1 and M2 estimated the concentration of chlorophyll in the water, with the M2 model demonstrating greater efficacy in detecting cyanobacteria compared to the M1 model.

Sentinel-2 images enable precise observation of variations in cyanobacteria concentration over time, facilitating the monitoring of seasonal changes and blooms.

The results of our study highlight the effectiveness of NDWI in identifying surface water zones and the M2 Chlorophyll-a model

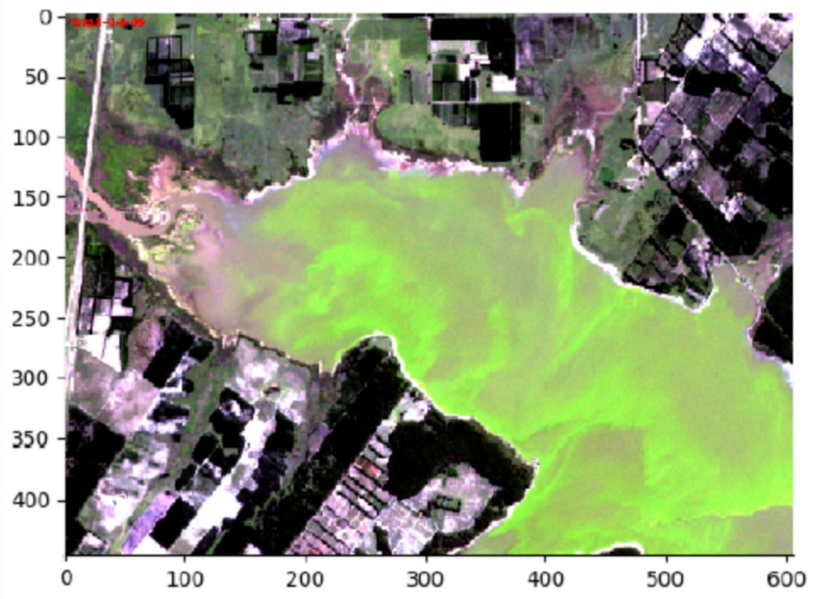


Figure 8. RGB image taken during an algae bloom

in detecting cyanobacteria. Combining these methods with on-site measurements is likely to provide a robust tool for reservoir monitoring and management.

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References

Aguilera, A., Haakonsson, S., Martin, M. V., Salerno, G. L., Echenique, R. O., 2018. Bloom-forming cyanobacteria and cyanotoxins in Argentina: A growing health and environmental concern. *Limnologica*, 69, 103–114.

Berdugo Muñoz, A., 2016. Análisis multiespectral de imágenes satelitales para evaluar variaciones espacio-temporales en la calidad del agua del embalse el Guájaro, Atlántico. PhD thesis, Facultad de Ciencias Ambientales, Universidad de la Costa.

Bonasea, M., Baz´an, R., Pagot, M., Pinotti, L., Ledesma, C., Rodríguez, C., 2014. Utilización de imágenes Aster y Landsat para el monitoreo de la concentraci´on de clorofila-A en el embalse de los Molinos, Córdoba, Argentina. *Biología Acuática*, 69–77.

Bonilla, S., Haakonsson, S., Somma, A., Gravier, A., Britos, A., Vidal, L., De León, L., Brena, B., Pírez, M., Piccini, C., Martínez de la Escalera, G., Chalar, G., González-Piana, M., Martigani, F., Aubriot, L., 2015. Cianobacterias y cianotoxinas en ecosistemas límnicos de Uruguay. *INNOTEC*, 10, 9–22.

Bordet, H., 2019. Factores reguladores de floraciones potencialmente tóxicas en el Embalse de Salto Grande. PhD thesis, Universidad de Buenos Aires.

Butler, N., Carlisle, J. C., Linville, R., Washburn, B., 2009. Microcystins: a brief overview of their toxicity and effects, with special reference to fish, wildlife, and livestock. *California Environmental Protection Agency, Sacramento*, 5.

Carrasco Vela, D. L., 2019. Teledetección y calidad de agua: una revisión de la literatura científica.

Comisión Técnica Mixta de Salto Grande, 2019. Niveles del embalse de salto grande. Recuperado de http://www.saltogrande.org/niveles.

Facciolo, G., 2019. MVAdenoising. https://github.com/gfacciol/MVAdenoising/blob/master/vistools.py. Retrieved on November 25, 2019.

Federici, M. T., Vallejos, M., Sim´on, C., Rovira, P., Ciganda, V., Rigamonti, N., Ferrari, G., 2022. Impacto de las cianotoxinas en la producci´on agropecuaria y el ambiente. *Revista INIA*, 68, 16–22. http://www.ainfo.inia.uy/digital/bitstream/item/16346/1/Revista-INIA-68-Marzo-2022-16.pdf.

Fournier, C., Quesada, A., Cirés, S., Saberioon, M., 2024. Discriminating bloom-forming cyanobacteria using lab-based hyperspectral imagery and machine learning: Validation with toxic species under environmental ranges. *Science of the Total Environment*, 932, 172741.

Gao, B.-C., 1996. NDWI - A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote sensing of environment,* 58(3), 257–266.

García Díaz, D., 2023. Aplicación de técnicas de aprendizaje automático a la monitorización de la calidad de masas de agua mediante técnicas de teledetección. Phd thesis, Universidad de Cantabrica, https://repositorio.unican.es/xmlui/handle/10902/28313.

Goyenola, G., Meerhoff, M., Teixeira-de Mello, F., González-Bergonzoni, I., Graeber, D., Fosalba, C., Vidal, N., 2015. Monitoring strategies of stream phosphorus under contrasting climate-driven flow regimes. *Hydrological Earth System Science*, 19, 4099–4111.

Izaguirre, I., Procura, H., Bordet, F., Bazzalo, M., 2018. Variaciones espaciales y temporales de la comunidad fitoplanctónica y análisis particular de cianobacterias potencialmente tóxicas en el río Uruguay. *Jornadas sobre biodiversidad en el corredor del río Uruguay*, Paysandú.

Kruk, C., Martínez, A., Martínez de la Escalera, G., Trinchin, R., Manta, G., Segura, A. M., Piccini, C., Brena, B., Fabiano, G., Pirez, M., Gabito, L., Alc´antara, I., Yannicelli, B., 2019. Floración excepcional de cianobacterias t´oxicas en la costa de Uruguay, verano 2019. *INNOTEC*, 18, 36–68. [Date of Consultation: August 8, 2024].

McFeeters, S. K., 1996. The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *International journal of remote sensing,* 17(7), 1425–1432.

Pérez, B., Serna, A., Delgado, J., Caballero, M., Villa, G., 2020. El programa copernicus aplicado a la producción y gestión de la información geoespacial. Technical report.

Rouse, J., Haas, R., Schell, J., Deering, D., 1973. Monitoring vegetation system in the great plains with erts. *Third ERST Symposium, NASA SP351*, 1, 309–317.

Veneros, J., García, L., Morales, E., Gómez, V., Torres, M., López-Morales, F., 2020. Aplicación de sensores remotos para el análisis de cobertura vegetal y cuerpos de agua. *Idesia (Arica)*, 38(4), 99–107.