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Space-time monitoring of water quality in an eutrophic reservoir using SENTINEL-2 data - A case study of San Roque, Argentina

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ABSTRACT

Eutrophic reservoirs are characterized by excessive presence of plant and algal growth due to favourable environmental conditions, temperature, light and nutrients. Human activities accelerate this phenomenon and provoke dramatic changes to the aquatic ecosystems. The monitoring of water quality of these ecosystems and the study of the effects they have on the environment demand a large amount of spatial and temporal information, which is almost exclusively provided by Earth Observations (EO). This study uses a large temporal series of Sentinel-2 (S2; 2016 till 2019) images to characterize the temporal and spatial distribution of chlorophyll-a [Chl-a] in San Roque Reservoir, Cordoba Province, Argentina. A robust method that combines empirical modelling of [Chl-a] and data mining analysis is employed. Model results showed significant fit ($R^2 = 0.77$) between [Chl-a] measured in the reservoir and the ratio between the NIR and red bands of S2. An analysis of spatio-temporal patterns demonstrated that [Chl-a] distribution in San Roque is complex and influenced by seasonal changes, aeolian forces, hydrodynamic flows, bathymetry, water levels, and pollution sources. The study also found a correlation between algae bloom events and areas with extreme levels of [Chl-a] (>850 mg/m3) in the water body. Additionally, advanced data mining tools such as slope analysis and spatial anomalies indexes, identified regions in the reservoir where water quality had improved or deteriorated. The results show the added value of using large Sentinel-2 data series to assess the concentration of Chlorophyll-a in eutrophic reservoirs over a variety of spatial and temporal scales.

1. Introduction

Eutrophication is the process in which the primary production of a water body increases with the contribution of organic matter and nutrients. This high productivity of biomass, at all trophic levels, produces qualitative and quantitative changes in the phytoplankton community and leads to algae blooms (Wetzel, 2001). The increased pressure on water ecosystems resulting from anthropogenic exploitation and pollution, in combination with climate and rainfall changes, affects the ecological integrity of water resources (Dörnhöfer et al., 2018; Whitehead et al., 2009).

In order to accurately assess water quality and to supply safe drinking water, quantitative indicators and regular monitoring are essential to detect these changes in time and space and mitigating their impacts on water supplies and ecosystem services (Martin et al., 2016). Chlorophyll-a concentration [Chl-a] is a common quantitative indicator of water quality and algal blooms. It is traditionally monitored with *in situ* sampling and laboratory analyses, which requires extensive work and time and, as a result, limits the scales over which samples are collected (Ferral et al., 2017). In addition, during blooms when the spatial distribution of phytoplankton biomass is high, conventional water sampling is insufficient to determine where and how algae spread

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(Schaeffer et al., 2013).

The use of remote sensing and satellite based on multispectral imaging became increasingly common to answer the need for finer time and spatial monitoring of stressed aquatic ecosystems. It has been widely used to monitor inland, coastal and estuaries water across different global regions (Papenfus et al., 2020; Tyler et al., 2016; Neil et al., 2019). Large variety of algorithms have also been developed to retrieve [Chl-a] values from several Earth Observation (EO) missions, including MODIS (Abbas et al., 2019), MERIS (Palmer et al., 2015), Landsat 8 (Guachalla Alarcón et al., 2018), Sentinel-2 (Yadav et al., 2019) and recently also for Sentinel 3 (Moses et al., 2019). However, retrieving [Chl-a] and algae species from turbid waters through satellite remote sensing remains a challenge due to the low spatial resolution of many sensors and the presence of other optically active compounds. Turbid inland waters may contain dissolved and particulate matter, including detritus, suspended sediments, and colored dissolving organic matter (CDOM), which impedes [Chl-a] retrieval. This optically complex framework is associated with more temporal and spatial variation of water quality parameters, which are influenced by weather changes, biological composition, and physical characteristics (Soomets et al., 2020).

The Sentinel-2 (S2) program, with its five-day temporal resolution, new red edge and NIR bands, and spatial resolution at least three times greater than that of previous optical programs, opened up a new era in aquatic monitoring (Ambrose-Igho et al., 2021; Caballero and Navarro, 2021; Ha et al., 2017; Tawfik et al., 2014). This study proposes a monitoring scheme for bio-indicators of turbid water eutrophication using S2 data. In particular, the proposed methodology integrates multi-temporal S2 images and [Chl-a] *in situ* data to create an empirical model and a spatial-temporal [Chl-a] series. It uses data mining to detect pollution sources and evaluate mitigation systems, including artificial aeration, using spatial and temporal patterns. Finally, it uses different indices, combined with spatial and temporal information of [Chl-a], in order to detect anomalies such as bloom events and their sources.

2. Study area

San Roque reservoir is situated at 600 m over sea level in Punilla Valley, Córdoba Province, Argentina. Its shallow barycenter is located in the coordinates 31° 22′ 56″ S, 64° 27′ 56″ W (Fig. 1). The temperate weather of the region is characterized with summer rainfall in the range of 400–1000 mm and an annual average of approximately 720 mm (Rodríguez et al., 2006). The reservoir has only a single emissary, the Suquía River. Its drainage area, of about 1750 km^2, receives contribution from four tributaries; the San Antonio and Cosquín rivers and Los Chorrillos and Las Mojarras streams. These rivers and streams are the origin of organic and inorganic materials in the sub-basins of the reservoir (BUSTAMANTE et al., 2007).

The water column of the reservoir is considered monomictic (Helmbrecht and López, 1997; Morillo et al., 2002); which means that a convective mixing happens only once a year during the cold seasons. On the other hand, during the hot seasons, two water layers separated by a well-defined thermocline are created by thermal stratification. The average historical temperature measured in the water surface varies from a media of 12^{o}C in winter, 18^{o}C during fall, 20^{o}C in the spring and 25^{o}C during the summer and the winds are predominant from the south and north (Rodríguez et al., 2006).

The dam in the reservoir is used for water supply for the city of Córdoba, flooding control, hydroelectric energy and recreational activities. Some low scale grazing is present in the basin but the main anthropogenic activities are concentrated in the urban areas of the cities Carlos Paz (31° 24′00″S, 64°31′00″W) and La Falda (31°05′00″S, 64°30′00″W) where only limited sewage treatments are available. During summer, the population of these cities are three times more because of tourism. In addition, during the dry seasons (winter, fall and spring) large wild fires leave burnt areas in the basin and its ashes eventually end as nutrients in the water of the lake (German et al., 2018). These seasonal variation in natural and anthropogenic processes provoke changes in the composition of the phytoplankton and increase the risk for development of harmful algae species including Cyanophites, which can be toxic to human health (Germán et al., 2016).

As San Roque reservoir is the most important source of water supply in the Province, the Córdoba Water Management authorities invest large efforts in its purification. This includes the implementation of Landsat and MODIS program in monitoring [Chl-a] in the reservoir (Germán et al., 2017; Ferral et al., 2018; Guachalla Alarcón et al., 2018) together with massive and frequent *in situ* measurements. Other mechanical solutions are also considered in the attempt to mitigate the eutrophic processes like the diffusers that has been installed in the eastern part of the reservoir (Fig. 1) (Antenucci et al., 2003). One of the objective of this work is to evaluate the effectiveness of these mitigation measures.

3. Materials and methods

3.1. Field data

The field data used in this work was collected and generated from 2016 till 2019 in the context of a monitoring program carried out by the Ministry of Water, Environment and Public Services of Córdoba province (Germán et al., 2016; Ferral et al., 2017). Eight monitoring stations were selected to evaluate the effect of the aeration system on the quality of the water. Three stations are located at the active part of the diffusers (“Zona A”, “Zona B” and “Garganta”), one station at the center of the lake (“Centro”) and four stations near the entrance of the tributaries (“SAT 1”, “SAT 2”, “SAT 3” and “SAT 4”) (Fig. 1). Three other stations monitored by the National Institute of Water are also included in this study. These stations are located in the center of the lake (“Centro”) and at the entrance of San Antonio River (“DSA”) (see Table 1 for coordinates). Sampling, storage and analysis activities of water samples were carried out according to Standard Methods for the Examination of Water and Wastewater (Rice et al., 2012). After quality check, only 9 measurement campaigns coinciding with the passes of the satellites and 35 samplings of [Chl-a] were considered. Specifically, nineteen measurements were used in generating the model and 16 measurements were used in validating the processing scheme (Table 1).

3.2. Satellite data

All Sentinel-2 A and B images acquired over the area from launching date in 2015 till the end of August 2019 were used in this research. In total, 132 images with less than 30% cloud cover were automatically downloaded with the module `i.sentinel.download` (evelopment Team. G, 2019). Fig. 2 shows the annual and monthly distribution of the acquisitions. Although most of the images (about 40%) were acquired in the year 2017/2018 and mainly during the summer and winter periods, the number of available images are sufficient for statistical analysis of the annual and seasonal trends of the extracted variables.

The images were atmospherically corrected using the package Sen2cor (LouisVincent et al., 2016) available at the SNAP toolbox. Leaving radiance calculated using window of 3 × 3 pixels around the location of each sampling station was used to obtain the mean spectra of the water. Land areas were masked out using the Copernicus Global Surface Water product available online.[1] Only areas labeled “Permanent Water” (12 months present) in the Seasonal product of 2018 were considered for further processing.

3.3. Regression model: chlorophyll-a estimation

In order to choose best predictors, Pearson correlation was

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[1] https://global-surface-water.appspot.com/download.

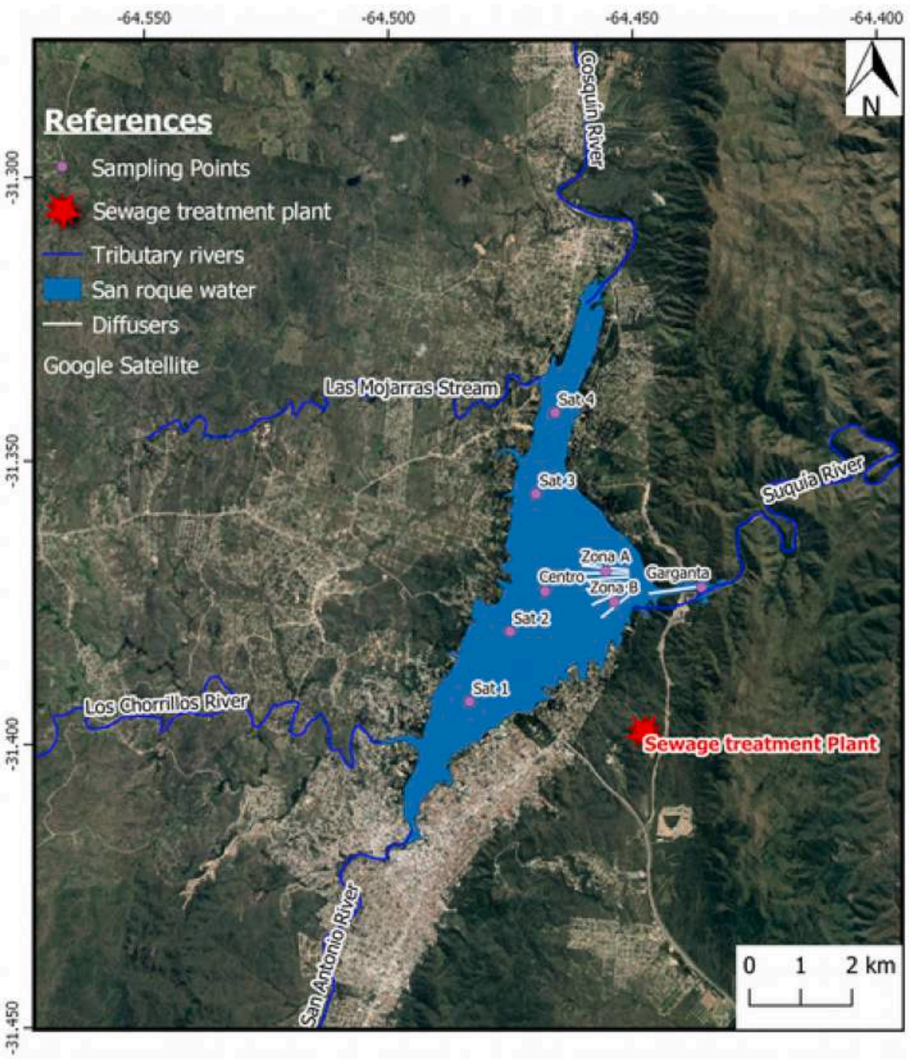


Fig. 1. Map of San Roque reservoir showing the locations of sampling points, diffussers, sewage treatment plant and tributary rivers.

calculated over all the S2 bands or over selected combinations (i.e logarithms, indexes ratios) against lab [Chl-a] from 7 selected dates of the Modelling Data set (Table 1). Bands or bands ratio that presented significant correlations (i.e. p value less than 0.01) were used to build linear models. Finally, the model with the highest R^2 and lowest Root Mean Square Error (RMSE) values was chosen for mapping the [Chl-a] concentration in the region of interest. The model was validated using the control data set presented in Table 1.

3.4. Series analysis

After validation, a ratio model was used to build temporal series of [Chl-a] using the entire data set (i.e 132 S2 images). These temporal series were used to describe the spatial and temporal distribution of [Chl-a] in the water body by implementing the `r.series` module of GRASS GIS software (evelopment Team. G, 2019). Specifically, this module provides several statistical functions for extracting temporal behaviour of variables and obtaining their tendency along a selected period. Besides basic statistics functions as average, median, maximum values and standard deviation, it is also possible to calculate the linear regression R coefficient (slope) in order to extract a trend along the reservoir. This calculation is applied to different time periods and the rate is expressed in mg/m3 per unit of time. With respect to the annual variation, the dates were separated following hydrological years 2016/2017; 2017/2018 and 2018/2019 (from August to July of the following year) and calculated linear regression in each of the selected years. To identify extreme events originated from algae blooms,a threshold based on local statistic was defined using the temporal-spatial average and percentiles distribution. Other spatial patterns within the reservoir were extracted using the Mean Normalize Spatial Index (MENSI) (Ferral et al., 2017), to detect spatial anomalies in the values of [Chl-a]. Originally, this index was developed in order to compare variables that share temporal dispersion but vary in the spatial domain. The index is calculated as follows:

$$MENSI = \frac{\sum_{j=1}^{M}\left(\frac{C_i}{\sum_{i=1}^{N} C_i / N}\right)_j}{M} \tag{1}$$

where j is the index of the date, i is the pixel number, M is the total dates, N is the total number of pixels and C is the value of the pixel, i.e. [Chl-a].

In this case, if the [Chl-a] in pixel i for a selected date is similar to the periodic average concentration, MENSI will approach to one. If the pixel shows higher concentration than the average, MENSI will be higher than 1. The other way side, if the pixel value is lower than the average, MENSI will be lower than 1. The index is therefore a good indicator for water quality conditions. Areas with index values lower than 1 contain better water quality conditions than other parts of the lake. For this analysis, the dates were divided by cold and warm season and MENSI indexes

Table 1
[Chl-a] (mg/m^3) measured in sampling stations along San Roque reservoir.

Date	Sampling Point	LAT	LON	[Chl-a]
Modelling Data				
26/01/2016	DSA	−31.41557	−64.49695	103.0
22/02/2017	Centro	−31.3742	−64.4694	127.1
22/02/2017	Garganta	−31.3731	−64.4391	197.1
22/02/2017	Zona A	−31.3708	−64.4569	53.8
22/02/2017	Zona B	−31.3762	−64.4552	288.5
22/02/2017	Sat 1	−31.3935	−64.4851	27.6
22/02/2017	Sat 2	−31.3812	−64.4767	132.2
22/02/2017	Sat 3	−31.3570	−64.4710	94.7
22/02/2017	Sat 4	−31.3427	−64.4668	56.7
16/08/2017	Centro	−31.3812	−64.4767	2.8
16/08/2017	Sat 2	−31.3812	−64.4767	9.8
16/08/2017	Zona A	−31.3708	−64.4569	14.9
21/11/2017	Sat 4	−31.3427	−64.4668	45.2
24/07/2018	Centro	−31.37667	−64.46517	10.0
24/07/2018	DSA	−31.41557	−64.49695	14.0
28/08/2018	Centro	−31.37667	−64.46517	33.0
14/11/2018	Garganta	−31.3731	−64.4391	69.38
14/11/2018	Zona B	−31.3762	−64.4552	52.3
14/11/2018	Sat 1	−31.3935	−64.4851	84.0
Validation Data				
04/02/2019	Centro	−31.3812	−64.4767	54.9
04/02/2019	Garganta	−31.3731	−64.4391	56.46
04/02/2019	Zona A	−31.3708	−64.4569	100.24
04/02/2019	Zona B	−31.3762	−64.4552	33.11
04/02/2019	Sat 1	−31.3935	−64.4851	55.21
04/02/2019	Sat 2	−31.3812	−64.4767	69.02
04/02/2019	Sat 3	−31.3570	−64.4710	86.93
04/02/2019	Sat 4	−31.3427	−64.4668	50.46
13/05/2019	Centro	−31.3812	−64.4767	5.09
13/05/2019	Garganta	−31.3731	−64.4391	4.08
13/05/2019	Zona A	−31.3708	−64.4569	5.49
13/05/2019	Zona B	−31.3762	−64.4552	5.66
13/05/2019	Sat 1	−31.3935	−64.4851	4.69
13/05/2019	Sat 2	−31.3812	−64.4767	7.08
13/05/2019	Sat 3	−31.3570	−64.4710	8.64
13/05/2019	Sat 4	−31.3427	−64.4668	11.58

calculated for both subgroups.

4. Results

4.1. [Chl-a] model

The Pearson analysis found a significant correlation of 0.789 between the concentration of [Chl-a] and S2 Band 8 (NIR: 0.842 nm) and S2 Band 4 (Red: 0.665 nm) ratio. Following these results, a linear regression model was developed using 60% of the modelling data according to:

$$[Chl-a] = -5.57 + 80.13^{*} band8/band4 \tag{2}$$

This linear model obtained a fit of 0.77 (R^2), a significant p-value < 0.0001 and root mean square error (RMSE) of 34.07 mg/m^3 (Fig. 3, left). These results encouraged the mapping of [Chl-a] for each S2 image of the lake using the model.

Validation of the retrievals using the validation data set obtained significant accuracy of 0.82 (R^2), p-value < 0.0001 and RMSE of 13.53 mg/m^3 (Fig. 3, right).

4.2. Temporal analysis

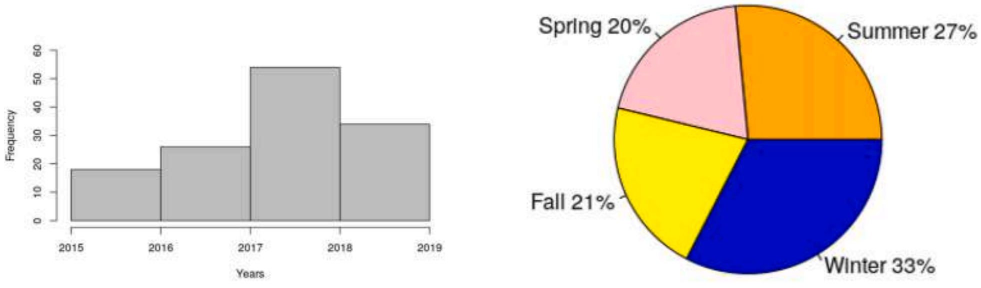
Fig. 4 plots the [Chl-a] concentrations in “Centro” station during the entire time series. The plot shows a typical behaviour of biological organism that is regulated by temperature with high concentration peak in the summer (December to March) and low concentrations during winter (June to September). The plot also shows that several extreme concentration values of over 100 mg/m3 were measured during the summers of 2017, 2018 and 2019.

Fig. 5 presents the results of basic statistics calculated for the retrieved [Chl-a] using the linear model for the entire S2 data set. During the observed period, 2016–2019, the average concentration value of [Chl-a] in the reservoir is 50–65 mg/m^3 (Fig. 5 (a)). As previously studied (Germán et al., 2016), these average values are relatively high and corresponded to eutrophic-hypertrophic conditions.

The median values (b), which are robust against the high deviation and in a way represent the natural behaviour of the reservoir, shows high concentration of [Chl-a] along the shores (>60 mg/m^3) and eutrophic conditions (>50 mg/m^3) in most of the water body, except for the north part where lower values of <40 mg/m^3 are observed. Concentration values of <40 mg/m^3 are also observed in locations near the diffusers. High concentration values (>750 mg/m^3) (Fig. 5 (c) and (d)) are observed in zones that are directly influenced by the contributions of the tributary rivers, San Antonio at the south and Cosquín at the north part of the basin. This is a common characteristic of eutrophic lakes that present high standard deviation of [Chl-a] near the entrance of the tributary rivers (Bresciani et al., 2019). Other patterns of very high [Chl-a] (>850 mg/m^3) are observed in different locations in the water body (Fig. 5 (c) and (d)). These values are originated from scums of algae during bloom events (Guachalla Alarcón et al., 2018; German et al., 2019).

4.2.1. Inter annual behaviour

Fig. 6 shows the median concentration of [Chl-a] for the hydrological years 2016/2017; 2017/2018 and 2018/2019 (from August to July of the following year). The results show large inter annual variations. In the years 2016/2017 and 2018/2019, the north part of the reservoir has been characterized by low [Chl-a] (<40 mg/m^3), while the shores and San Antonio area by high concentration values (>60 mg/m^3). On the other hand, in the year 2017/2018 almost the entire area of the lake has been characterized by high [Chl-a] (>60 mg/m^3). Fig. 7 shows that this



(a) (b)

Fig. 2. (a) Annual distribution and (b) seasonal distribution of the Sentinel-2 A and B images downloaded for the area during the study period.

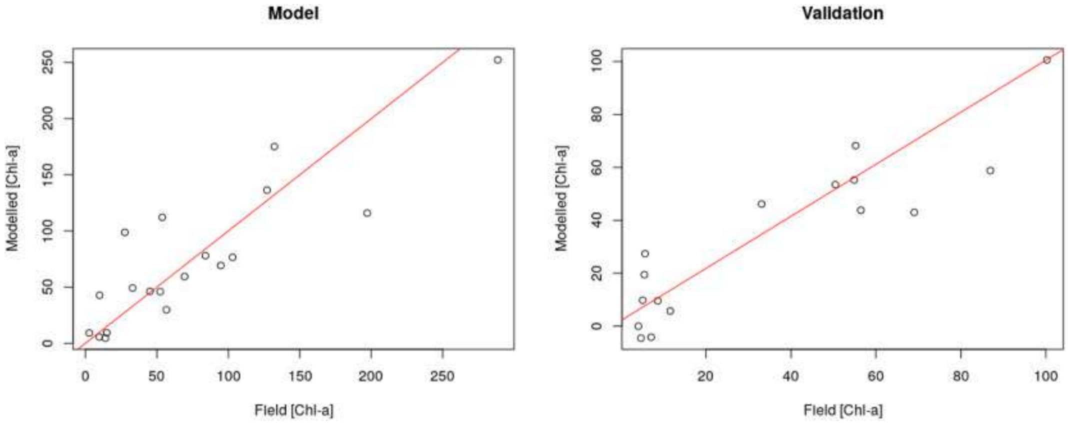


Fig. 3. Linear regression between field and modelled data using the training data set (left), $R^2 = 0.77$. Linear regression between field and modelled data using the validation data set (right), $R^2 = 0.82$.

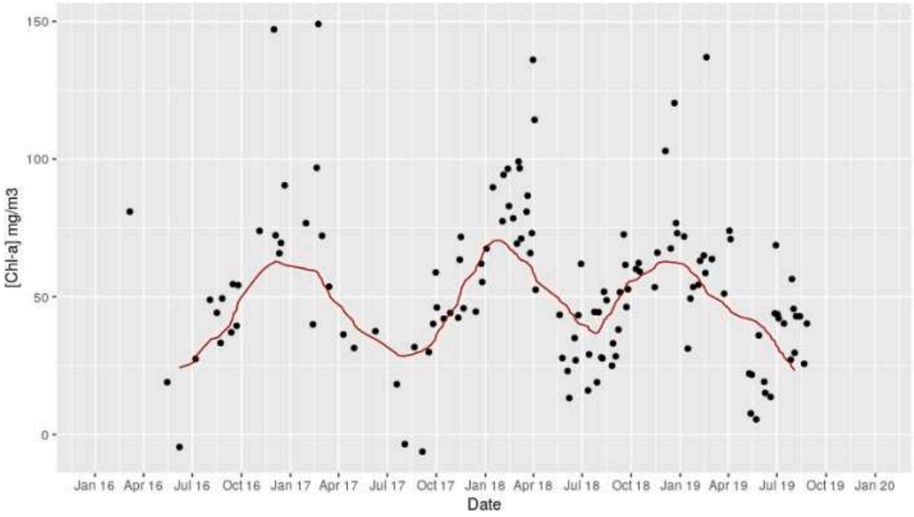


Fig. 4. [Chl-a] concentration in "Centro" (black dots) and smoothed non-parametric trend (red line) calculated over the entire data series using Dine of (Beckers and Rixen, 2003). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

inter-annual variation is mainly influenced by the water level in the reservoir. In 2017/2018 the water level was very low in comparison to the hydrological years 2018/2019 and 2016/2017. Another pattern visible in Fig. 6 is the influence of diffusers near its area, where [Chl-a] values are lower during the three years analyzed.

The annual linear regression R coefficients (slopes) that were calculated for each pixel for the selected years (Fig. 8), exposed other spatial variations within the reservoir. Fig. 8 (a), shows patterns of extreme positive values (>2 mg/m^3 month) in the center of the lake that are originated from the presence of algal blooms during the summer of 2017 and specifically during the passage of S2 on the 22/02/17 (German et al., 2019). Other high slopes are observed in this year (a) attributed by more nutrient and sediments that have been flooded into the basin with San Antonio River. In 2017/2018 (b), patterns of high positive tendency (>2 mg/m^3 month) are observed in the north part of the basin, attributed to the Cosquín River input. In 2018/2019 (c), only thin patterns of positive tendency are observed, and negative values (<- 1 mg/m^3 month) are present in the north. This means that in this hydrological year the water quality in the reservoir was better in comparison to the precedent two years due to the high water level and dilution process (Fig. 7). The water level in the reservoir has also influenced the source of the pollution. This can be observed in the hydrological year 2016–2017 (Fig. 8 (a)), where high slopes values were observed in the entrance of San Antonio river when the water level was relatively high. In 2017–2018 (b) when the water level was low, high slopes values were observed in the entrance of the Cosquín river. This area presents shallow bathymetry and concentrates more pollutants when the water level is low.

4.2.2. *Seasonal behaviour*

Table 2 presents seasonal statistics analysis of recorded lab [Chl-a] in each station. The results for the warm season show very high median and standard deviation values in "SAT 3", "SAT 4", "Zona A" and "Centro" that indicate that strong variation in the [Chl-a] is distinguished in the center to north part of the reservoir. On the other hand during the cold seasons, there are no large differences between the median and the standard deviation values.

The median of the satellite derived [Chl-a] was also calculated and mapped for the summer and winter (Fig. 9). As expected and already observed with other sensors in (Alba et al., 2020), the median values are higher during the warm season. During the summer (Fig. 9 left), extreme high values of [Chl-a] (>80 mg/m^3) are observed along the shores and at the entrance of San Antonio river. During winter, low values of [Chl-a] (<30 mg/m^3) are observed along the shores and near the entrances of the two rivers. In the two seasons, the satellite derived [Chl-a] values are higher in the center of the lake in comparison to its peripheries. Only during the summer, local low [Chl-a] values are observed near the diffuser. This indicates that they are having a positive impact on the

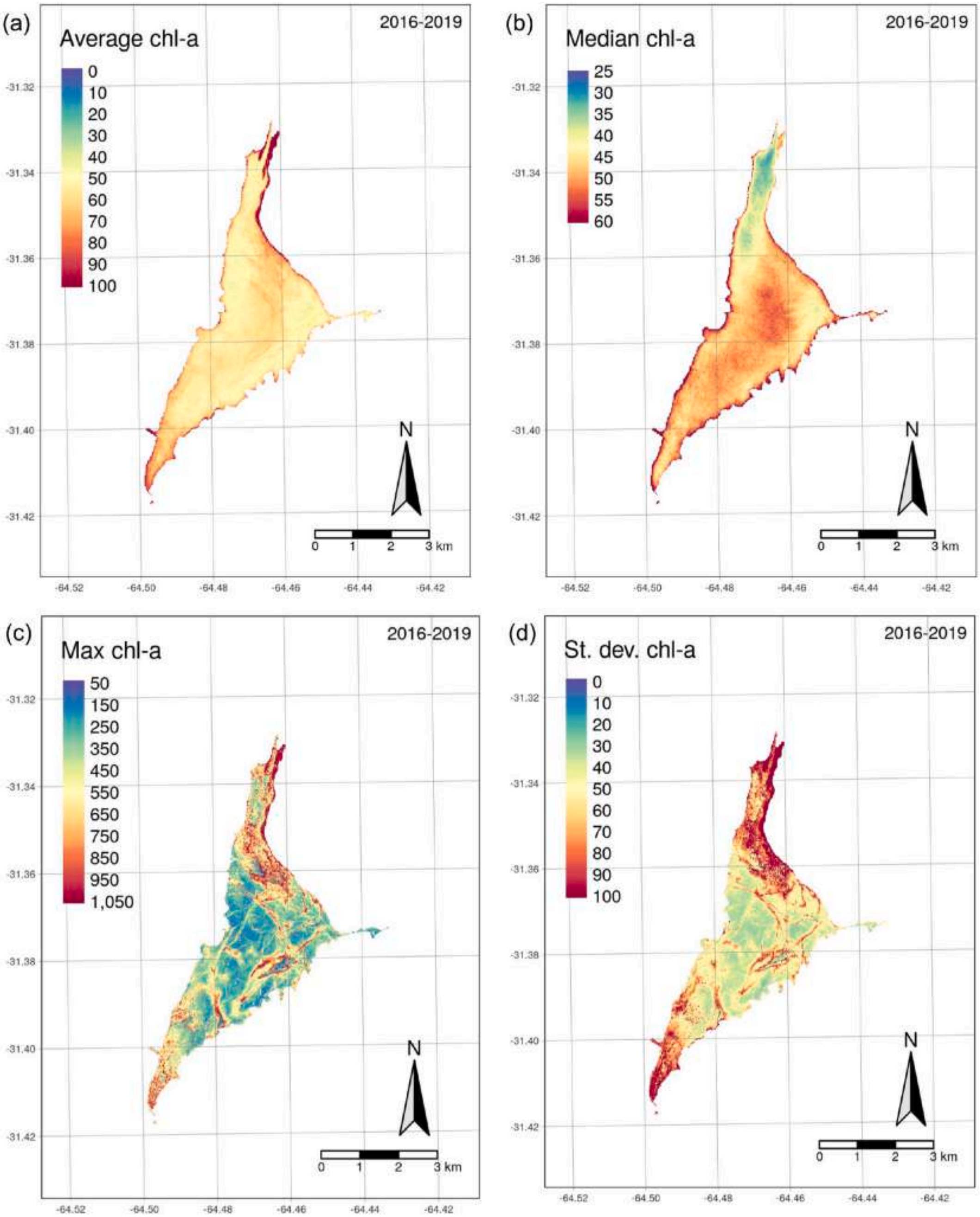
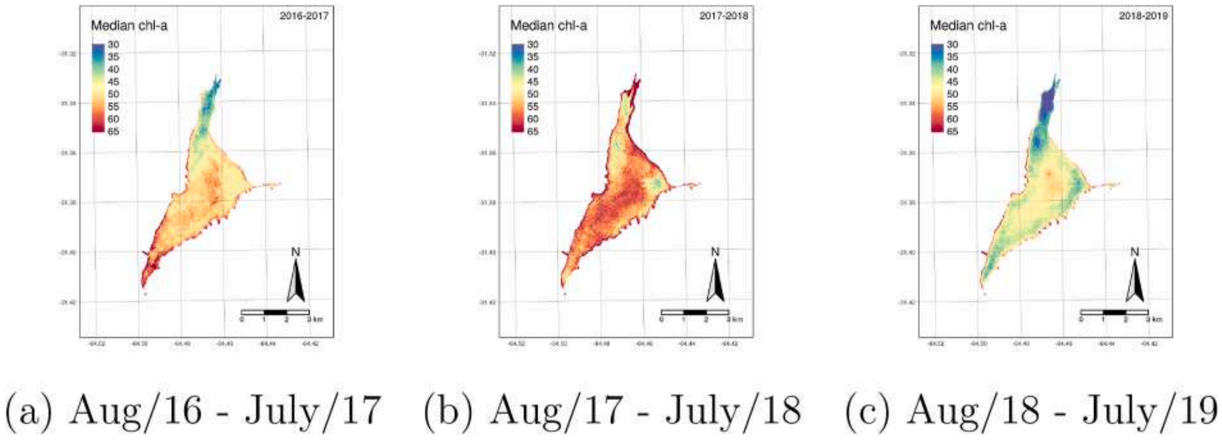


Fig. 5. Statistics analysis for the retrieved [Chl-a] using the complete data set of S2 from 2016 till 2019. Values are in mg/m^3.

water quality, as also observed in the yearly median maps (Fig. 6). The field data shown in Table 2 supports this observation. Lower median values were measured in the "Garganta" and "Zona B", during the observed warm season. Also during the year 2017–2018 when the water quality is the worst, the difference in [Chl-a] values are even more evident in the areas near the diffusers (Fig. 6 (b)). During the cold season, when the diffusers are only occasionally operated, field measurement show degradation in the water quality near "Garganta" (Table 2). The water quality is actually similar to the polluted areas near the tributaries "SAT 1" and "SAT 4". According to (Curtarelli et al., 2015), in reservoirs where thermal stratification and mixing are key drivers of algal bloom growth and dispersion, artificial aeration systems are good solutions as they were designed to break the thermal stratification and favour the mixing of water (Antenucci et al., 2003). However, the field data shows that "Zona A" has the lowest water quality condition (Table 2). This is probably due to aeolian forces in the center of the lake that are stronger than the diffusers and diminish their influence [5, 27]. Therefore, it means that the selected technical solution has only local influence.

Statistical slopes were calculated in order to analyse the seasonal evolution in the values of [Chl-a] (Fig. 10). During summer, fall and spring the lake is characterized with negative slope values and patterns of high positive values in different locations. In summer and spring, the high positive slopes values (>2 mg/m^3 year) are located mainly in the northern (Cosquín and Las Mojarras rivers entrances) and eastern (sewage treatment plant coast) parts of the reservoir. Also during warm season, in the dam wall area ("Garganta") high positive slope values (>2 mg/m^3 year) are observed. During fall, only thin patterns of positive slopes values are observed in the center part of the water body. During winter, the trend is changing and positive slope values are observed in



(a) Aug/16 - July/17 (b) Aug/17 - July/18 (c) Aug/18 - July/19

Fig. 6. Yearly median concentration of [Chl-a] in San-Roque reservoir.

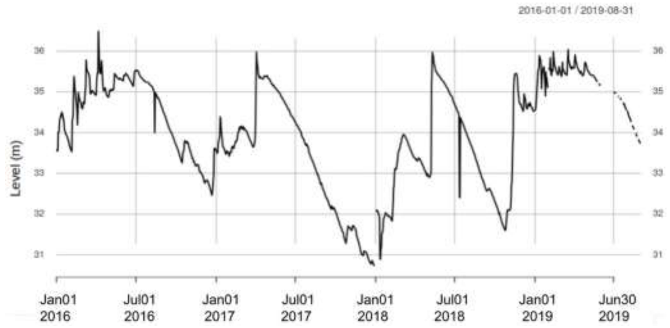


Fig. 7. Water level measured in the dam during the period January 2016 till January 2018. Data are collected by the Province of Cordoba and available online at https://www.cba.gov.ar/nivel-de-diques-y-embalses.

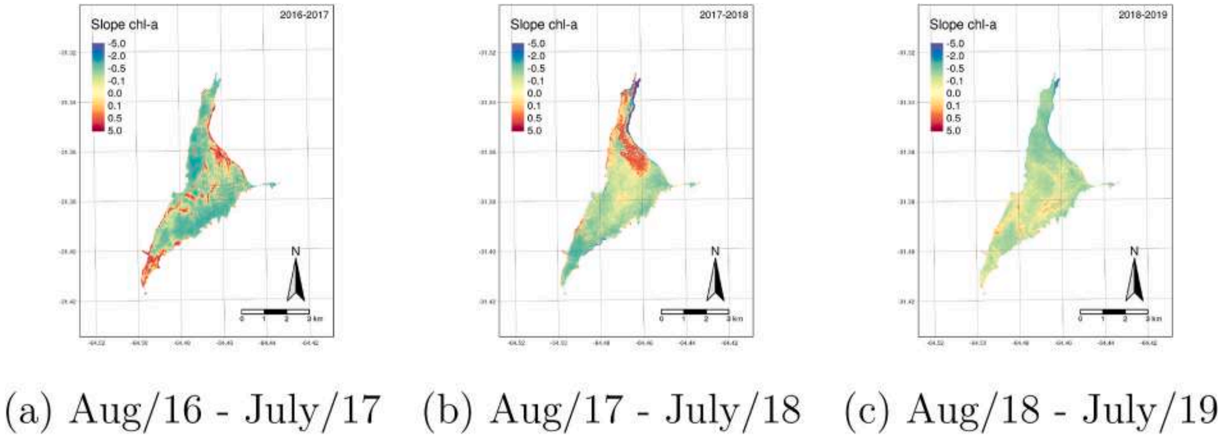
all the area of the lake except for near the main tributary rivers (San Antonio and Cosquín). With less extreme events at this time of the year, this result could be indicating a general degradation tendency caused by the growth of population settlements near the reservoir. This is making pressure on the water resources during the whole year (German et al., 2018) and the available sewage treatment is insufficient.

The seasonal analysis shows that summer is clearly the season with the highest [Chl-a], especially near the entrance of San Antonio river (Fig. 9 (a)). The contribution of nutrients by this tributary river is very high during a rainy summer when the temperatures are high and the touristic activities along its shores are elevated (German et al., 2018). In addition, strong river inflow enforces high charged river streams to release their nutrients at the entrance of the Cosquín river where the bathymetry is shallow. The hydrodynamic behaviour of San Roque causes this biomass to float from the entry of the Cosquín river to "Garganta" (dam area) and along the eastern coast (Fig. 9 (a)) (Alexander and Imberger, 2009). This phenomena can be also observed during the spring (Fig. 10), where patterns of high slopes values are observed in the northern part of the lake, near the Cosquín river.

Also, in the warm seasons (summer and spring), there are areas with positive seasonal slopes (Fig. 10) at the eastern-coast and at the southern part of the diffussers (greater in the summer than in the spring). This variation is probably due to the sewage treatment plant which its emissary is located near the eastern-coast, inside the water body (Fig. 1). During the warm season, when the touristic population is tripled, the pressure on the plant is high and provoke failure in performing tertiary treatment of nutrient decantation (German et al., 2018). This deteriorated treatment has not prevented the development of algal blooms near the Cosquín River (north) and the sewage plant (east) in the studied warm seasons.

4.3. *Spatial patterns enhancement*

The MENSI was calculated for the two subgroups of dates of warm (spring-summer) and cold (fall-winter) seasons. This gave us two results presenting different anomalies patterns, presented in Fig. 11 (a) and (b), respectively. Fig. 11 shows that the shorelines of San Roque have low water quality in both seasons. Nevertheless, areas near the diffusers and near stations "SAT 3" and "SAT 4" show better water condition than the



(a) Aug/16 - July/17 (b) Aug/17 - July/18 (c) Aug/18 - July/19

Fig. 8. Annual slope of [Chl-a] for the years 2016/2017; 2017/2018 and 2018/2019 (from August to July of the following year). Values are in mg/m^3/month.

Table 2
Seasonal statistics of lab [Chl-a] (mg/m^3) recorded in the sampling stations.

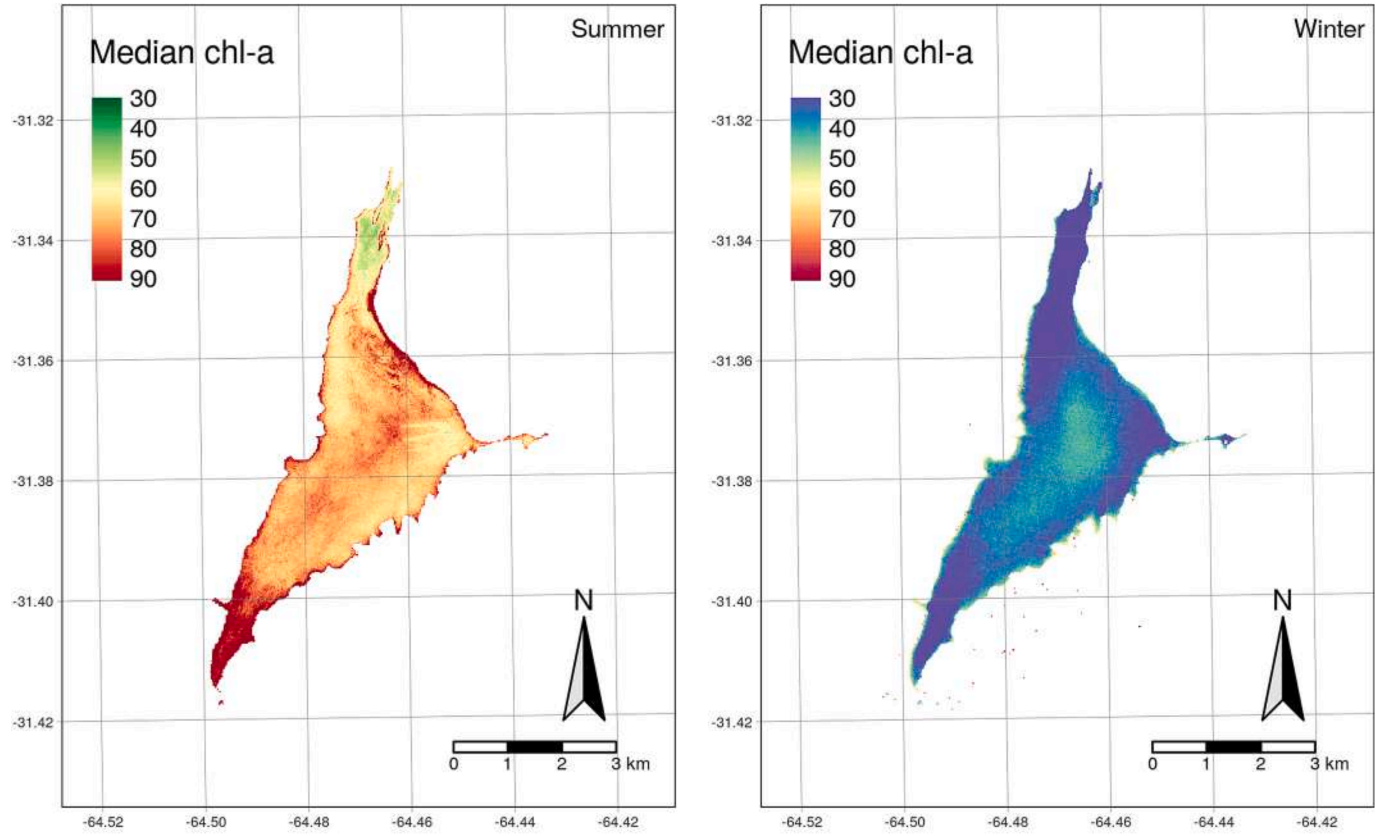
Site	Median	Min	Max	Stand. Dev.
Warm Season				
Centro	91.90	5.36	379.9	122.95
Garganta	62.13	32.1	197.1	59.32
SAT 1	59.10	27.6	248.8	75.24
SAT 2	73.42	20.00	132.2	39.79
SAT 3	124.70	42.8	432.5	157.79
SAT 4	72.90	1.00	703.12	231.81
Zona A	100.24	5.38	494.9	161.63
Zona B	65.60	4.57	288.5	100.95
Cold Season				
Centro	13.52	2.77	65.30	26.82
Garganta	20.5	4.08	80.90	28.89
SAT 1	22.6	3.03	64.00	25.56
SAT 2	19.4	7.08	63.40	25.96
SAT 3	11.76	8.64	75.10	37.50
SAT 4	20.19	9.40	56.80	21.90
Zona A	17.015	5.49	69.80	24.23
Zona B	11.755	5.66	43.60	17.24

average in both seasons. During the warm seasons, Fig. 11 (a), high values of the index can be observed in the entries of Cosquín and San Antonio rivers. However, the center of the water body contains average water condition (i.e. index values similar to 1). On the other hand, during the cold season, Fig. 11 (b) shows similar pattern but with different conditions. The water quality in the center of the lake is worst than the average (i.e. MENSI values are higher than one). And in contrast to the behaviour found during the warm season, index values lower than 1 can be found at the entries of the main tributaries rivers.

In order to identify extreme [Chl-a] values originated from algae blooms, a 'bloom threshold' was defined using temporal-spatial statistics. Different percentiles were calculated to the spatial mean temporal series, derived for each date. Finally, a value between the percentile 97 and 98 was chosen equal to 150 mg/m3. Even though it is considered a very high value ((Carlson, 1977), (Paul, 1987)), the large range of [Chl-a] in the reservoir, makes it adequately to detect extreme events (i.e the temporal mean of the spatial minimum value for all the dates is 8.28 mg/m3 while the temporal mean of the spatial maximum values is 634.07 mg/m3).

Fig. 12 shows that during maximum 12 days (i.e. 0-9 percentages) between 2016 and 2019, the concentration of [Chl-a] in most of the lake was higher than the bloom threshold. The figure also shows that the frequency of this anomaly is higher in the entries of the main tributaries. Some high frequency can also be observed in the north-east coast of the basin and at the entry of the Los Chorrillos river in the south-west part of the reservoir. Fig. 12 also shows that the frequency of this anomaly decreases near the "Garganta" and the diffusers, reinforcing the result shown in section 4.2 that they are having a positive but only local effect in the water quality.

The results in Fig. 12 also show that the variation in water quality is low in the center of the lake, which can be also observed in Fig. 5 (c), (d). This was also observed even in the warm season, when most of the algae blooms are developed, as it can be seen in Fig. 11 (a) (center index values similar to 1). Similar results were found in previous study (Ferral, 2013; Ferral et al., 2017) analysing *in situ* data, which encourage and emphasises the capability of Earth Observation (EO) remote sensing to monitor water quality.



(a)Median summer. (b)Median winter.

Fig. 9. Seasonal median values of [Chl-a] (mg/m^3).

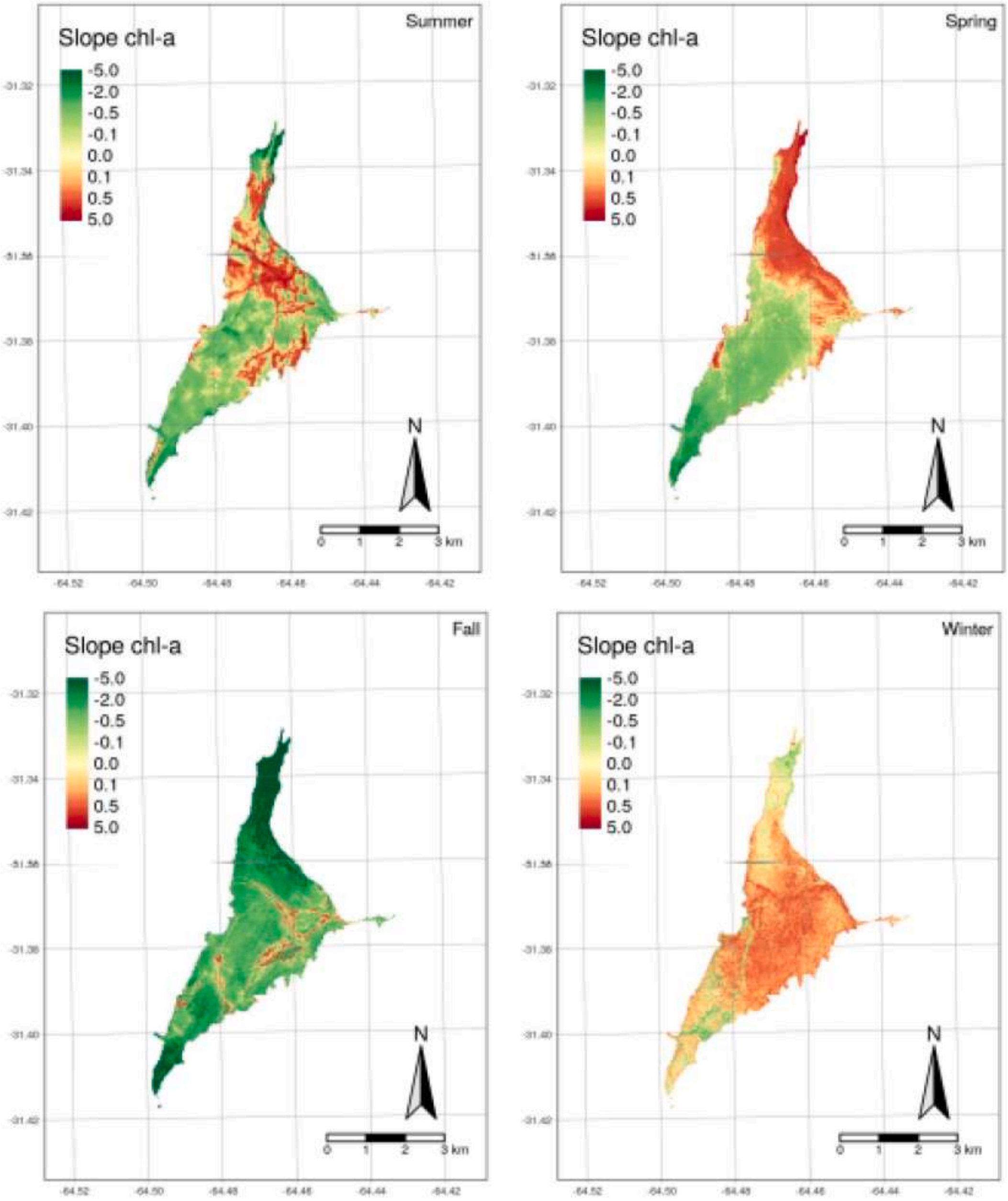


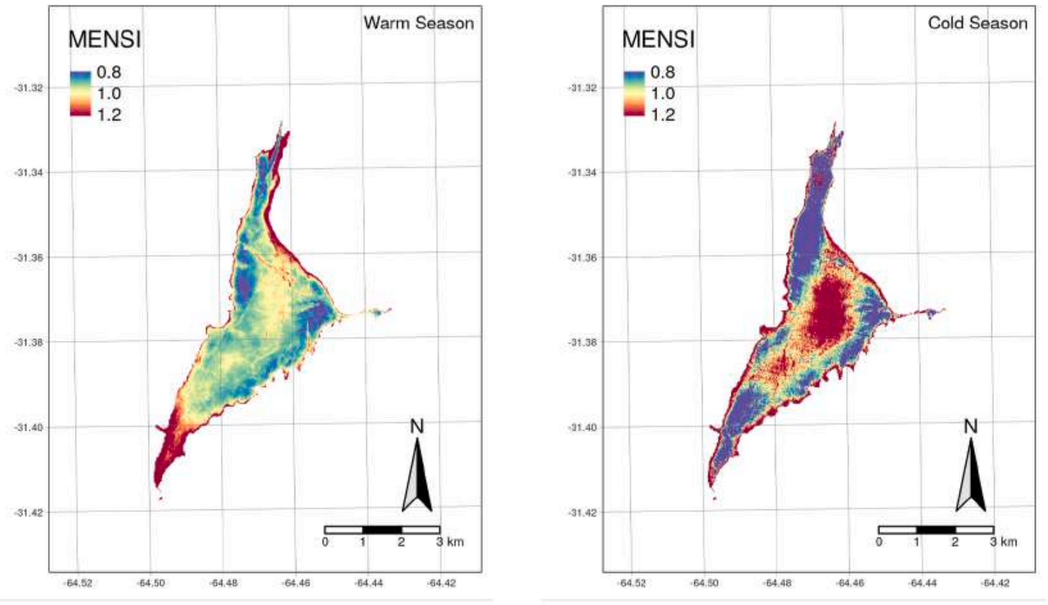
Fig. 10. Seasonal slope of [Chl-a].

4.4. Hydrodynamics and aeolian mechanisms

The spatial-temporal analysis presented in section 4.2 and 4.3 demonstrates that the distribution of [Chl-a] in San Roque is complex and dependent on seasonal changes, aeolian forces, hydrodynamic flows, bathymetry, water levels and pollution sources.

According to (Muchiut et al., 2019), north and south winds, which are dominant in the region, generate a high velocity layer of water in the same directions. This aeolian process drifts the scums and accumulate them at the two polar regions (north or south). This can be observed in Fig. 9 (a) and Fig. 12. In addition, water that is circulated in the northeast and southeast parts of the lake generate up-welling forces from the bottom of the lake that provoke turbulence and local flotation of biomass. These aeolian processes have been observed in other eutrophicate water bodies where up-welling forces in areas of shallow water produce re-suspension of sediments from the bottom (Bresciani et al., 2019; Lisi and Hein, 2019).

During rainy seasons (at the beginning of the spring or summer), the contributions of nutrients from the rivers by hydrological forces are stronger than the contributions maintained by aeolian forces. However, when the nutrients reach the center of the reservoir, they are displaced towards the north using strong water inertia forces driven by the wind. The effect of this process is observed in the median maps (Figs. 5, Figs. 6 and Fig. 9 (a)) and in seasonal slope maps (Fig. 10) explained in section 4.2.2. The effects of these seasonal processes can be also observed in the MENSI index map (Fig. 11). During the warm seasons (a), the water quality in the north and south coasts are low (i.e. index values higher than one) due to the contributions of the tributaries. During the cold seasons (b), the rivers flows are weaker and carry lower mass of nutrients that are discharged in the center of the lake. This results in high MENSI values and low water quality in the center of the lake.



(a) Warm Season. (b) Cold Season.

Fig. 11. Seasonal MENSI of Chl-a.

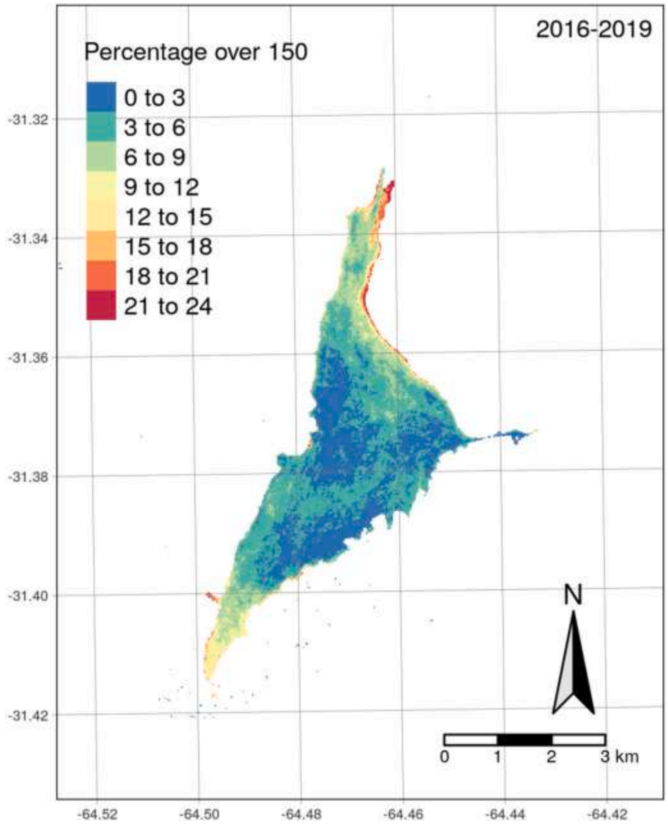


Fig. 12. Percentage of number of dates within the concentration of [Chl-a] was higher than 150 mg/m^3.

5. Discussion

Studying the spatial-temporal variability of water quality and algal blooms, is essential to understand the behavior of water systems under the constant stress produced by anthropogenic and meteorological impacts (XueAlan et al., 2020; Kim et al., 2021). This study benefits from the use of remote sensing data to understand the complex spatial temporal trends of [Chl-a] and bloom events, by data mining approach. Thanks to the better combination of spatial, temporal and spectral resolution of Sentinel-2, the main sources of pollution have been successfully identified as the areas where the water quality is deteriorating in different temporal scales. The results presented provided a first understanding of the different seasonal changes and the influence of external factors, as aeolian forces, hydrodynamic flows, bathymetry and water levels.

To the best of our knowledge, this kind of spatial temporal series study involving Sentinel-2, is novel. Research works typically focus on single date information (Caballero and Navarro, 2021; Potes et al., 2018; Ismail et al., 2019). The current methodology demonstrated that Sentinel-2 can be used to characterize the dynamics of algal blooms in aquatic environments using spatial temporal series of [Chl-a] estimation.

In this sense, empirical model of [Chl-a] continues to be the most common method to study water quality due to its simplicity and accuracy (Topp et al., 2020). The main disadvantage is that the model cannot be generalized to other water bodies or observation period (Topp et al., 2020). This study considered a wide range of field [Chl-a] (2.8 mg/m^3 - 288.5 mg/m^3) and large temporal data set for building the model. Considering the good fit and the low RMSE ($R^2 = 0.77$ and RMSE = 34.07 mg/m^3), the rich recorded data provides proper representation of the temporal and spatial distributions of [Chl-a] during the studied period. Moreover, the fit obtained is at the range of the ‘generalized mean fit’ ($R^2 = 0.76$; $\sigma = 0.184$) calculated in (Topp et al., 2020) using the results of 144 researches. Also, the accuracy (R^2) obtained and RMSE are at the ranges respectively reported by (Bresciani et al., 2019) and (Lin et al., 2018). This similarities in qualities to the results obtained in (Bresciani et al., 2019) and (Lin et al., 2018) are encouraging considering the large data set, extensive hydro-meteorological inputs and complex physics and machine learning algorithm the authors were implementing to construct their models. In general, the assumption in the research community is that models based on complex machine learning algorithm, physics, or manifold analysis obtained better fit and less errors than empirical models (Topp et al., 2020), (Bresciani et al., 2019).

The results presented in this research show that the ratio between the red and the NIR band of S2 are directly related to the [Chl-a]. This conclusion is not new and is supported by previous studies that used red and infrared bands to estimate the [Chl-a] in inland eutrophic waters ((Gitelson et al., 2008), (Gitelson, 1992), (Gitelson et al., 2007), (Gons, 1999), (Patra et al., 2016), (Germán et al., 2016)). This narrow spectral region is suitable for monitoring water quality using remote sensing as it is not affected by other vegetable pigments (Gitelson, 1992). It is however recommended to use spectral band ratios rather than a single band, in order to reduce the contributions of atmospheric irradiance and air-water surface effects (Ha et al., 2017; Topp et al., 2020).

Nevertheless, water quality and bloom events are more complex than only characterization of [Chl-a], so a multidisciplinary approach including different variables is recommended to understand this phenomena (Vaičiu¯tė et al., 2021). The data presented here showed that the poorer quality of the water in 2017 (Fig. 6 (b)) in comparison to the other two studied years (Fig. 6 (a) and (c)) is also related to the water level in the reservoir (Fig. 7). As also documented in (Lisi and Hein, 2019), during dry years in eutrophic lakes turbidity increases, while during wet years they become clearer, influencing directly in trophic status and algae species diversity. The worst water quality observed in this period, produced extreme algae blooms in large areas of the lake. Specifically, sampling campaign that took place on the 22/02/2017 measured very high concentration values of [Chl-a] (max: 288.5 mg/m^3 in “Zona B”) and identified the presence of cyanobacteria (*Microcystis aeruginosa*) and also *Ceratium Hirundinella* (German et al., 2019). The cyanobacteria was predominant in the areas near the entrance of the tributaries, while the Ceratium was predominant in the center and near the dam (German et al., 2019). These two species as well as *Anabaena/Dolichospermum* are commonly found in the reservoir during bloom events (Rodríguez et al., 2006). While Cyanobacterias can generate toxins and produce Harmful Algal Blooms (HAB’S) the *Ceratium Hirundinella* species are not dangerous to human health but produce bad odours, brown water color and generates plugging in water filters.

Sentinel-2 is a very valuable resource for identifying and quantifying bloom events due to its high frequency and availability. Moreover, in the current global situation due to the COVID-19 pandemic, where field sampling is more limited than usual, remote sensing becomes even more essential in the monitoring of water bodies (Yunus et al., 2020). Additionally, *in situ* sampling offers limited information about time and space, when compared to the spatial-temporal series analysis presented in this work. The synoptic information provided through resulting maps is indicative of the whole water surface and can be easily interpreted by local authorities in order to support management and remediation strategies.

Deep comprehensive analysis of inland water quality is needed for proper rehabilitation and protection of water supply. The findings of this study offer various approaches to strengthen the operational monitoring of water quality in San Roque reservoir, using Sentinel-2 mission. The anthropogenic impacts mainly due to untreated sewage waste waters have to receive significantly attention if this deteriorating process aims to be addressed. The study demonstrated that Sentinel-2 satellite data provide sufficiently accurate information to detect priority areas in the basin where attentions must be focused.

Future work will be directed on developing early warning response systems. Specifically, the spatial and temporal model will be enlarged and integrated with climatic, chemicals and anthropogenic variables that influence the cycle of [Chl-a]. In the frame of this future research, the data collected by a Hydro-Meteorological Station installed recently inside the reservoir (Prystupczuk et al., 2018) will be included, along with more field data collected in order to improve the accuracy of the model.

6. Conclusion

A complex hydrological model is required to understand the spatial and temporal processes which occur within an eutrophic reservoir. The [Chl-a] is only one indicator to measure the eutrophic level of water body and the statistical analysis presented in this manuscript is only partially addressing this need. Nevertheless, the developed methodology provides a first insight to the processes that affect this type of reservoir. The spectral based empirical model and the multi-temp statistical analysis performed in this study, allowed us to identify the tributary entries to San Roque as the main source of nutrients. Specifically, high content of organic matters carried from the watersheds by the flows of Cosquín and San Antonio Rivers are the main pollution sources of the reservoir. Inter-annual and seasonal patterns of [Chl-a] identified by the model follow similar trends obtained with field measurements, indicating a good performance of the model. In addition, data mining tools as slope analysis and MENSI index were found very useful in identifying regions in the reservoir where water quality is improving or deteriorating. During the cold season, the index results showed the center of the lake as the area with worst water quality while during the warm season the worst conditions are observed in the north-east and south regions (near the tributaries rivers). The defined space-time threshold (i.e. 150 mg/m^3) and the map created using its range, enable the detection of extreme events as algal blooms.

This research shows the effectiveness in using multi-temporal S2 series to explore trends in the [Chl-a] at different scales. The high time frequency of S2 provides accurate information for early warning and monitor evolution of blooms events, required for water management. The robust work scheme developed in this study is based on open source EO data, algorithms and analysis methods and therefore it can be replicated and implemented easily and without cost to other water bodies with field monitoring. This scheme was used to asses the influence of the sewage treatment plant and the capacity of the diffusers. The data generated in this study can be integrated into regional models for water quality prediction, strategies and decision making of water management.

Ethical statement

The authors declare that we have followed all ethical practices in relation to the development, writing, and publication of the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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