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An application of C2-Net atmospheric corrections for chlorophyll-a estimation in small reservoirs

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ABSTRACT

This study assesses Sentinel 2 remote sensing data for estimating chlorophyll-a concentrations in 32 small reservoirs located in the Spanish region of Extremadura. The atmospheric correction algorithms C2RCC, C2X, and C2XC were used to obtain chlorophyll-a estimations. In-situ measurements of chlorophyll-a were collected from ninety-four water samples in the study area, and their values were used to validate the satellite-derived estimates. The results showed that the C2RCC atmospheric correction algorithm outperformed the other two algorithms, with a Mean Absolute Average Error (MAAE) of 4.79 mg/m^3 for non-hypertrophic reservoirs. C2X and C2XC algorithm performed inaccurately, with extreme RMSE and MAAE values. Spearman correlation coefficients are good for the three methods applied. The findings could be of interest to regional water management authorities and researchers in monitoring water quality in small reservoirs.

1. Introduction

The quality of inland freshwater bodies is considered one key environmental issue due to the threats water masses suffer from climate change and human activities (Gurlin et al., 2011)– (Khan et al. et al., 2014). This concern has been shown by multiple academic and political institutions at the highest international levels, as the Sustainable Development Goals prove (Mostert, 2003). However, the accurate monitorization of parameters and pollutants often imply costly, time-consuming processes that depend on in-situ measurements (Richardson, 1996), (Raman and Twait, 1994). Water quality control implies the measurement of many parameters like total suspended matter, transparency, or algae and phytoplankton. These are key elements that, along with surrounding information from human settlements, cattle farming and agriculture, health, or tourism, can provide a holistic approach on how to keep and manage healthy levels for the preservation of biodiversity along with social and economic development for communities depending on lakes, rivers, and reservoirs (Fernández Rodríguez, 2021)– (Sánchez-Martín et al., 2020).

To overcome the above-mentioned constraints remote sensing, traditionally used for oceanic and coastal waters, has been added to the methodologies used for inland water masses monitoring in the last decades. This is possible considering its latest advances in passing periods, space resolution and bandwidth variety, and because of the improvements in accessibility to current free systematic data from Landsat-8/9 and Sentinel-2 constellations. These satellites are operated by the National Aeronautics and the Space Administration (NASA) and the European Space Agency (ESA) respectively. The latter has indeed opened new potential for monitoring water quality in smaller water masses due to its high spatial resolution, radiometric resolution, and the development of specific processing software Sentinel Application Platform (SNAP) (ESA and "SNAP, 2023). However, achieving accurate retrieval of specific parameters can be challenging, despite estimate calculations being possible by means of indicators and algorithms (Alawadi, 2010)– (Tong,

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Feng, Zhao, Xu, Zheng). Due to the original applications of the sensors of these satellites on land or large ocean masses, inland water treatment requires a greater effort in terms of the use of different regions of the spectrum, since the percentage of extraction of reflectance in water can be below 20%, as in the case of the visible-near-infrared (VIS-NIR) region (WangIOCCG, 2010), while elements of the atmosphere can reach up to 90% of the reflectance. This is especially important for complex inland water masses, known as Case 2 waters (Gholizadeh et al., 2016), where optically active substances (OAS) like minerals, and microbubbles play an important role and do not covary with the phytoplankton levels. For this reason, correcting the contributions of constituents such as gases and aerosols is a crucial issue when analyzing images for water control purposes. Case 2 waters encounter a bigger complexity given the variety of OAS as chlorophyll and algae, Total Suspended Matter (TSM), or Color Dissolved Organic Matter (CDOM) that can produce both supplementary reflectance and absorption (WangIOCCG, 2010).

The abovementioned atmospheric corrections (AC) are hence an important step that can help retrieve accurate estimations of water reflectance. However, several processors have been developed in the last decades, and previous research focuses both on the application and evaluation of the different corrections (Gholizadeh et al., 2016). Pereira-Sandoval et al. (2019) evaluated the performance of six simple, different, free algorithms on Level 1 Sentinel-2 images (Top of Atmosphere) in Valencia, Spain for nine small-sized reservoirs.

The present work is part of a research project for the detection of chlorophyll-a concentrations with remote sensing techniques. The overall aim of the project is to evaluate different methods for the obtention of water quality parameters in reservoirs in the region of Extremadura, in western Spain. The region has 41,635 km^2 and a population of one million inhabitants in 2023, with an eminently rural settlement system. Two main river basins are located in Extremadura: the Tagus and the Guadiana basins. In addition, the region lies between the northern plateau and the southern plateau, on the Atlantic slope. Its topographic relief, population distribution and hydrological system have made the construction of numerous dams and reservoirs possible, which now are essential for the economic and social activities of the region. In total, Extremadura has more than 300 reservoirs, most of them being small, with a surface area below 1 km^2 (Sistema de Información Territorial de Extremadura (SITEX), 2022). Given the large number of reservoirs, the population density and the economic constraints of the region, the study of remote sensing techniques for their monitoring is crucial for the efficiency of quality control processes.

1.1. Previous works

The use of remote sensing for land and water monitoring is not new, and satellite sensor images have been applied since the launch of the first NASA Landsat and Nimbus satellites (Baker and Smith, 1981)– (Shoaf and Lium, 1976). However, some datasets have proven to be applicable to different states and characteristics of specific water bodies, like oceans, which makes criteria difficult to extend to broader water mass types. Previous research has used remote sensing products along with algorithms and water quality indices, to assess the best monitoring practices.

Some previous researchers have applied empirical models to model inland water quality assessment. These models imply in-situ samples and band ratio values relationship, with the use of regression analysis that provides specific algorithms for optically different water bodies (Masoud, 2022) or neural network and machine learning models (Fragoso Campón, 2021)– (Niroumand-Jadidi et al., 2021). These empirical models can help complement in-situ sampling methods, especially in multitemporal studies, according to Ansper and Alikas (2019). Thanks to the Landsat missions and other satellites, it is possible to develop multitemporal monitoring over several decades (Cao et al.).

One of the most recent semi-empirical models employs AC methods to estimate turbidity and Chl-a concentrations using the derived automatic products. The authors in (Pereira-Sandoval et al., 2019) assessed the applicability of ACOLITE, iCOR, Sen2Cor, Polymer, C2RCC, and C2X, finding Polymer, C2RCC, and C2X to be the best-performing processors when comparing to in-situ sampling and satellite reflectance. In a second research (Radin et al., 2020), found C2RCC to correlate better with in-situ samples because of the low turbidity level of the studied reservoir. For the Spanish inland water, the authors proposed a reservoir classification according to the Chl-a and Secchi values, by which they evaluated the best AC performance for each trophic type of reservoir. AC have also been used to find representative sampling sites depending on the recurrent patchiness (Lehmann et al., 2021).

Other researchers have performed inland water bodies assessment using multiband indices, where band combinations address specific constituents. Some named indices are the Floating Algal Index, the Normalized Difference Chlorophyll Index (NDCI) (Mishra and Mishra, 2012), the Normalized Difference Suspended Sediment Index, and the Maximum Chlorophyll Index. Other indices specifically applied for Chl-a concentration include Two and Three Band Algorithms (2BDA and 3BDA) (Watanabe et al., 2018), Fluorescence Line Height (FLH) (Buma and Lee, 2020), (Zhao et al., 2010), and Surface Algal Bloom Index (Alawadi, 2010). These indices have been successfully used to identify algal blooms. During the last years, have focused on the evaluation of a wide variety of band combinations for the chlorophyll-a and turbidity determination. In (Zhan et al., 2022), forty band combinations were applied for the retrieval of chlorophyll-a concentration values, and twenty-four for the study of turbidity. It would be of great interest to test the methodologies considering both regional aspects and size and shape of reservoirs.

In summary, the objective of the study is to test the applicability of Sentinel 2 images to monitor small reservoirs water quality in Extremadura.

2. Materials and methods

2.1. Study area and in-situ samples

To develop this study, data from thirty-six freshwater reservoirs in the region of Extremadura (Fig. 1), for a period between 2017 and 2022, were obtained from the Regional Government data. The similarity among them, and the fact that they are managed by the

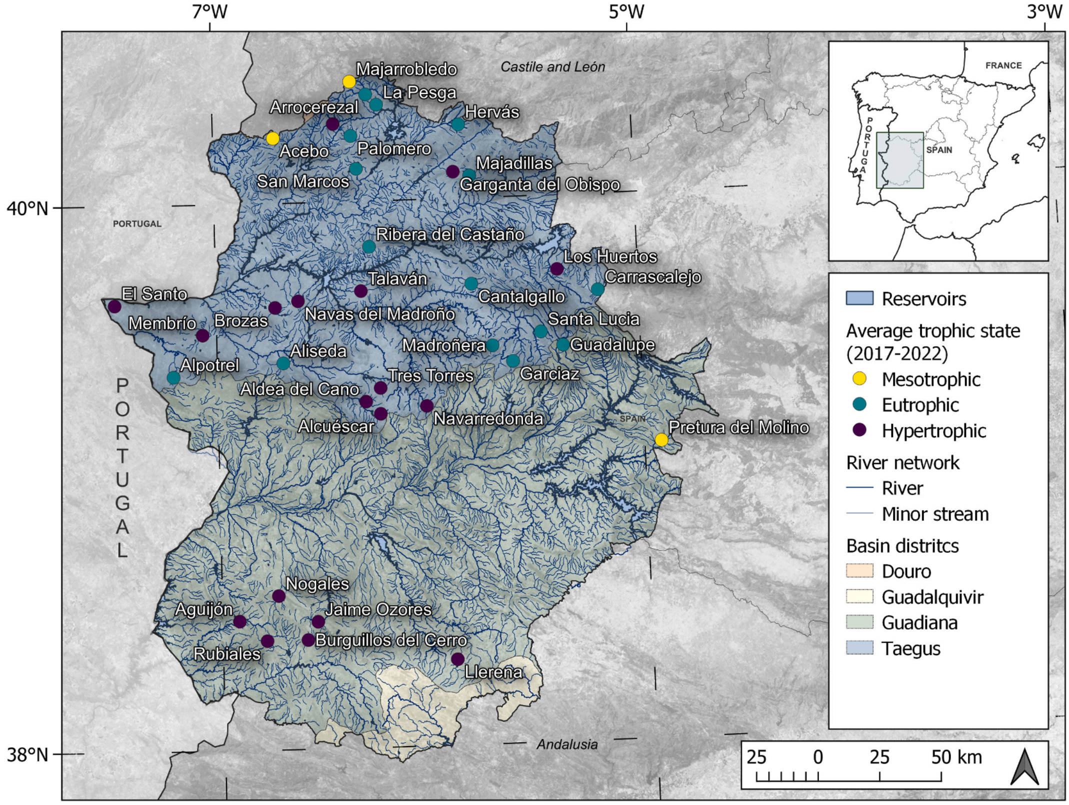


Fig. 1. Map of Extremadura showing all small reservoirs considered for the study area selection.

same administration must be noted, for that assures the in-situ measurement methods homogeneity. Fig. 1 reservoirs have been categorized following Pereira-Sandoval et al. water types, according to their parameters remote sensing response, as shown in Table 1 (Pereira-Sandoval et al., 2019). The reservoirs are controlled and monitored following national and European rules and regulations (Mostert, 2003), and in-situ measurement reports include physical and chemical parameters (Table 2). Chlorophyll-a concentration has been measured using a Fluoroprobe, which defines the concentration values in real time, allowing later evaluation at laboratory following multiparametric retrieval with the use of spectrophotometric procedures following ISO 10260 (Ministerio de Agricultura, 2013). This allows the analysis of the presence and distribution of algae in-situ. Given its number and the extent of the region, reports include a diversity of altitudes and morphological and biological characteristics, and a variety of trophic states, from mesotrophic to hypertrophic. Besides the mentioned differences, all monitored reservoirs have a major relevance at the local level, for surrounding towns and villages. This, along with the topography and scarce pluviometry of the region, makes them generally small, which increases the interest in remote sensing methods evaluation, for that entails a bigger challenge given the need for adjacency effects assessment and avoidance. Out of all of them, thirty-two reservoirs have been chosen based on remote sensing data availability. Their corresponding orthoimages can be seen in Fig. 2.

2.2. *Remote sensing data*

Sentinel 2 is a two-satellite constellation with a swath width of 290 km, and relies on the Multispectral Instrument (MSI), a 12 bits multispectral sensor covering 13 different wavelength bands. The highest spatial resolution for visible (B2, B3, B4) and infrared (B8) bands is 10 m, and the lowest resolution, for coastal aerosol, NIR water vapor and cirrus (B1, B9 and B10) cover 60 m. The remaining bands have a resolution of 20 m. Fig. 3 shows the spectral configuration of the sensor. Sentinel 2 images, along with other Sentinel missions, can be found in the official website. To develop the validation of the in-situ samples, a set of 94 Top of Atmosphere (Level

Table 1
Classification scheme by water type applied over lakes and lagoons according to chlorophyll-a (Chl-a) concentration and Secchi Disc (SD) depth (Pereira-Sandoval et al., 2019).

Water Type	Description	Chl-a (mg/m^3)	SD (m)
1	Ultraoligotrophic to oligotrophic	< 2.5	> 3
2	Mesotrophic to eutrophic	2.5 - 25	0.7 - 3
3	Hypertrophic	> 25	< 0.7

Table 2
Descriptors of the reservoirs according to their trophic state: number of samples and number of valid S2 images, elevation (m), surface (km^2), ranges of chlorophyll-a surface values (mg/m^3), atmospheric pressure (hPa), water temperature (C°) and average Chl-a value for the 2017-2022 period.

Location	Samples	Valid Dates	Elevation	Surface	Chl-a	Pressure	Water Temp.	Ave. Chl-a	Trophic state
Tres Torres	5	4	435	0,25	[49,46-331,88]	[966,5-977,8]	[11,9-23,8]	169,55	Hypertrophic
Rubiales	4	3	502	0,06	[47,49-204,58]	[973,5-980,8]	[13,542-26,447]	99,42	
Aldea del Cano	5	4	388	0,81	[46,81-131,6]	[965,3-977,8]	[12,3-28,6]	83,06	
Jaime Ozores	11	9	438	0,23	[7,28-211,82]	[969,6-985,5]	[15,83-24,4]	77,99	
Burguillos del Cerro	5	4	470	0,33	[1,9-201,095]	[969,6-985,5]	[7266-27,095]	73,69	
Navarredonda	5	2	512	0,51	[3,39-164,61]	[967,2-991]	[14,09-27,064]	70,89	
Llerena	4	4	543	1,63	[30,43-147,12]	[931-948,7]	[14,94-28,42]	65,19	
Nogales	5	3	369	1,38	[26,83-96,46]	[966,8-981,5]	[14,59-16,46]	60,08	
Brozas	5	4	395	0,25	[36,57-113,38]	[966,6-985,6]	[14,773-25,38]	56,97	
Aguijón	5	3	386	1,67	[5,27-166,96]	[956-977,9]	[14,78-20,2]	56,86	
Alcuéscar	5	2	443	0,48	[12,35-206,8]	[965,3-977,5]	[12,87-27,58]	56,66	
Los Huertos	4	2	525	0,10	[26,69-70,55]	[976,2-992,6]	[9427-24,63]	48,30	
Membrío	3	1	327	0,27	[19,53-60,76]	[959,1-966,7]	[14,582-18,872]	41,57	
Garganta del Obispo	3	1	983	0,01	[0,97-85,33]	[972,1-994,5]	[7266-16,185]	29,40	
El Santo	3	3	286	0,07	[9,77-62,78]	[959,1-975,5]	[15,271-18,216]	28,66	
Navas del Madroño	5	3	416	0,18	[10,48-33,63]	[966,6-985,6]	[14,749-25,76]	27,04	
Talaván	11	10	360	0,39	[3-72,17]	[967,6-979,9]	[14,5-24]	25,42	
San Marcos	5	5	401	0,37	[6,3-35,68]	[976,3-993,8]	[13,481-24,5]	23,21	Eutrophic
Palomero	3	2	476	0,05	[2,35-44,83]	[975,1-993,8]	[10,43-19,99]	21,98	
Ribera del Castaño	3	1	435	0,16	[10,51-26,99]	[972,2-979,9]	[11,53-16,66]	19,46	
Alpotrel	3	3	500	0,38	[10,4-25]	[959,1-975,5]	[14,944-17,937]	17,84	
Madroñera	5	2	705	0,13	[3,57-38,93]	[966,6-991]	[12,44-15,74]	16,41	
Hervás	3	2	822	0,04	[8,42-19,42]	[968-987,6]	[8196-15,735]	13,59	
Aliseda	3	2	349	0,07	[8,64-14,32]	[968,2-976,6]	[14,3-16,7]	11,87	
Las Majadillas	3	3	605	0,17	[2,78-25,99]	[981,1-994,5]	[10,2-14]	11,31	
Santa Lucía	3	2	682	0,13	[4,22-11,94]	[971,3-978,6]	[10,7-12,5]	8,85	
Arrocerezal	3	2	556	0,03	[0,73-18,95]	[977,8-989,3]	[10-15,5]	8,79	
Garciaz	3	1	779	0,05	[4,33-16,42]	[982,3-991]	[12,2-18]	8,76	
Cantalgallo	3	1	490	0,13	[4,39-12,2]	[968,4-980]	[10-19,7]	8,26	
Majarrobledo	3	1	920	0,02	[0,4-20,48]	[971,6-983,3]	[8-14]	7,72	Mesotrophic
Pretura del Molino	3	3	491	0,25	[5,58-8,41]	[964,4-972]	[10,9-17,2]	7,04	
Acebo	4	2	563	0,10	[2,5-11,5]	[970,2-985,8]	[9,5-19,11]	6,13	
Total	138	94	-	-	-	-	-	-	-

1C) images were downloaded and resampled to 10 m using the Sentinel Application Platform v 9.0. Images selection criteria have been based on cloud clearness conditions, with a temporary range of ±48 h 26% of images correspond to in-situ sampling days.

2.2.1. Atmospheric correction-derived chlorophyll-a value

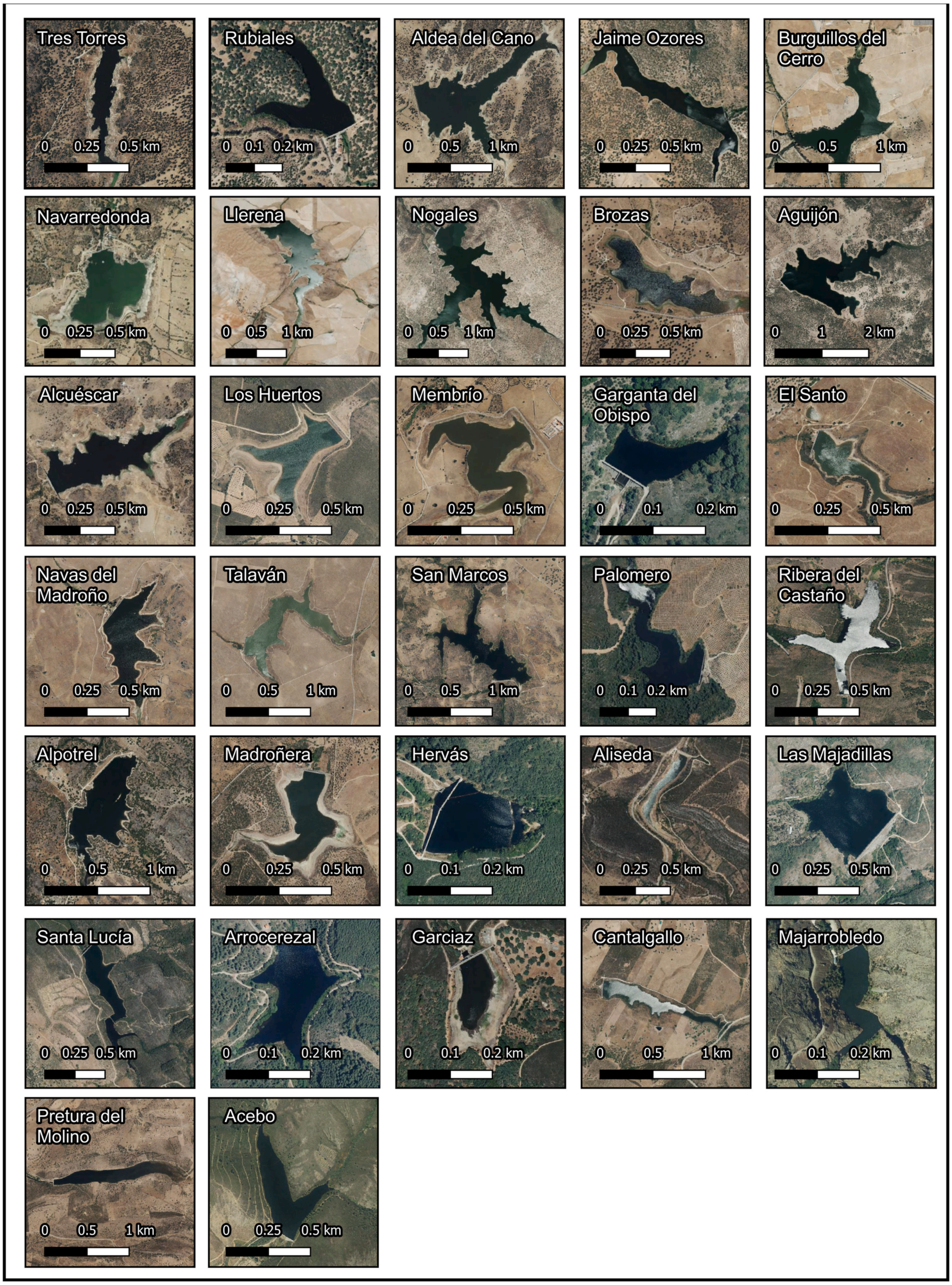
The C2RCC set of processors (C2-Nets) is an AC derived from the original Case 2 Regional (Doerffer and Schiller, 2007), based on an artificial neural network method. This processor is available within SNAP for a variety of sensors, including MSI. The output of the processors includes automatic products of chlorophyll-a and Total Suspended Matter, and the depth of the water column from which the 90% of the irradiance is derived (Soriano-González et al., 2022). It includes different processors depending on the neural network training ranges of the Inherent Optical Properties (IOPs). Case 2 Regional Coast Colour (C2RCC) is the original processor developed for the analysis of coastal waters. It was later complemented with C2X, a processor used for extreme cases, trained with higher absorption and scattering coefficients. C2X-Complex-Net (C2XC) is an intermediate processor, trained with values above C2RCC and below C2X absorption coefficients. Table 3 shows the maximum IOP training values for C2-Net processors according to Brockmann et al. (2016) and Ruescas et al. (Pereira-Sandoval et al., 2022). The minimum training values are 0.

For the AC parameters setting, salinity was set to 1 PSU for all reservoirs, while temperature, altitude, atmospheric pressure, and chlorophyll-a factor were established according to in-situ values, as described in Table 2. The reports contain chlorophyll-a values for a varying water column, between 0 and 15 m depending on the reservoir. However, the surface chlorophyll-a value (≈0.5 m depth) was used for both the chlorophyll-a factor and the subsequent statistical analysis. The rest of the values were set by default. For the concentration of constituents' bands, the extracted IOPs are transformed through the application of conversion factors. To convert a_pig to the Chl-a concentration, Chl-a exponent (exp_chl) and factor (fac_chl) are employed.

$$conc\_chl = a\_pig^{\exp\_chl} \times fac\_chl \tag{1}$$

2.2.2. Pixel value retrieval

For the pixel value retrieval, a Python script has been applied using the GDAL library. Extracting pixel values from each study area can be a time-consuming process, even using included geoprocessing tools using a GIS software. The function developed recovers the specific band value file (conc_chl). It then calculates the pixel coordinates of the specified point in the image using the ETRS89 UT-


Tres Torres
0 0.25 0.5 km
Rubiales
0 0.1 0.2 km
Aldea del Cano
0 0.5 1 km
Jaime Ozores
0 0.25 0.5 km
Burguillos del Cerro
0 0.5 1 km
Navarredonda
0 0.25 0.5 km
Llerena
0 0.5 1 km
Nogales
0 0.5 1 km
Brozas
0 0.25 0.5 km
Aguijón
0 1 2 km
Alcuéscar
0 0.25 0.5 km
Los Huertos
0 0.25 0.5 km
Membrío
0 0.25 0.5 km
Garganta del Obispo
0 0.1 0.2 km
El Santo
0 0.25 0.5 km
Navas del Madroño
0 0.25 0.5 km
Talaván
0 0.5 1 km
San Marcos
0 0.5 1 km
Palomero
0 0.1 0.2 km
Ribera del Castaño
0 0.25 0.5 km
Alpotrel
0 0.5 1 km
Madroñera
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Hervás
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Las Majadillas
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Santa Lucía
0 0.25 0.5 km
Arrocerezal
0 0.1 0.2 km
Garciaz
0 0.1 0.2 km
Cantalgallo
0 0.5 1 km
Majarrobledo
0 0.1 0.2 km
Pretura del Molino
0 0.5 1 km
Acebo
0 0.25 0.5 km

Fig. 2. Analyzed reservoir orthoimages. Source: Spanish National Air Orthophotography Programme (PNOA) (Instituto Geográfico Nacional, 2023).

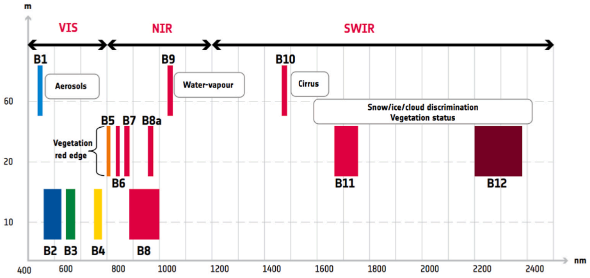

Fig. 3. Spatial resolution and wavelength of the 13 Sentinel 2 spectral bands ("ESA Bulletin 161, 2015).

Table 3
Inherent Optical Properties training maximum values of the C2-Nets.

IOP	Coefficient	C2RCC	C2XC	C2X
a_pig	Absorption of phytoplankton pigments	5.3	30.81	51
a_det	Absorption of detritus	5.9	17	60
a_gelb	Absorption of dissolved organic matter	1	4.25	60
b_part	Scattering of typical sediments	60	-	590
b_wit	Scattering of white (calcareous) sediments	60	-	590
b_tot	Scattering of white and typical sediments	-	1000	-

M29N coordinates. Finally, the function stores the maximum pixel value found within the surrounding 90 × 90 m buffer as the result. Fig. 4 depicts a workflow of the developed script.

2.3. Validation of chlorophyll-a values

Validation is essential to ensure that the remote sensing data is reliable and can be used for scientific or management purposes. Once algorithms were applied, the maximum value among the sampling point and the surrounding pixels was extracted. The data validation was performed using the chlorophyll-a band value (conc_chl), extracted from the previous step, and the in-situ samples.

On the one hand, Kernel density has been calculated. Kernel Density is an estimation of the distribution function of the stochastic variable Chl-a concentration, in this case. It is estimated based upon a linear superposition of unitary normal distribution function, centred in every data point. A bandwidth h is elected so maximum accuracy in estimation is reached. In general, the approximation to the distribution function is made by means of the following function:

$$\widehat{f}_h(x) = \frac{1}{n}\sum_{i=1}^{n} K_h\left(x - x_i\right) \tag{2}$$

Being n the number of specimens and h the elected bandwidth. K_h is the unitary kernel function, that, apart from normal, may be uniform function, as well as triangular, biweight, Epanichnikov (to minimize the Mean Square Error) or some others. As said, in this case, normal function is elected.

On the other hand, the Root Mean Square Error (RMSE) and the Mean Absolute Average Error (MAAE) were calculated for the conc_chl product derived from AC with the following formulae:

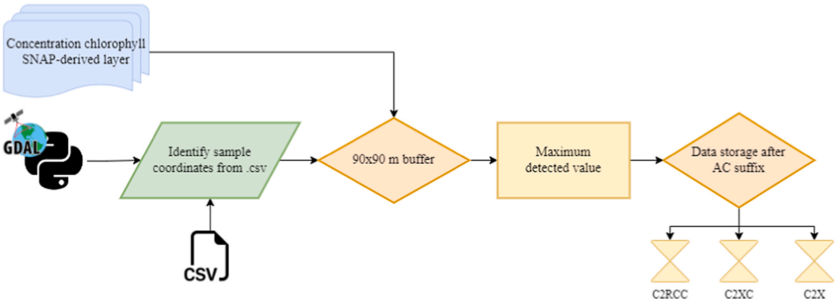

Fig. 4. Pixel value retrieval workflow.

$$RMSE = \sqrt{\frac{\sum_{1}^{N} (e_i - m_i)^2}{N}} \tag{3}$$

$$MAAE = \frac{1}{N}\sum_{i=1}^{N} |e_i - m_i| \tag{4}$$

where e_i is the sensed estimated value and m_i is the in-situ measured value.

Seegers et al. (2018) argue that while r^2 regression models are commonly used, these may be unsuitable for water colour algorithm performance assessment. Based on the evaluation of performance metrics for satellite data, MAAE is expected to provide a more robust validation of the chlorophyll-a data sets, as it is less sensitive to outliers. Finally, the nonparametric Spearman correlation was used to evaluate the association between the variables, since the data did not have a normal distribution, to analyze the algorithm behavior.

3. Results and discussion

After applying the abovementioned methodology, Fig. 5 shows a kernel density diagram with the application of each algorithm to the total data set. This diagram represents the kernel density with the in-situ values shown in red; C2-Net derived chlorophyll-a data are represented with a different shade of teal. In general, we can clearly distinguish the difference between the C2RCC processor, and the C2X and C2XC processors. Chl-a automatic products derived from C2RCC show a statistical behavior more similar to the in-situ values. On the other hand, the C2X and C2XC algorithms show a distribution with more or less the same mean but with a larger deviation (a platykurtic curve for these two distributions).

As said, Fig. 6, along with Table 4, shows very similar mean values, as well as skew and kurtosis of the distribution for C2RCC and in-situ values. On the other hand, C2X and C2XC present a quite platykurtic behavior, with a strong variability in results. For the mesotrophic and eutrophic group, the in-situ data and C2RCC variables have similar means and standard deviations, between 13.26 and 13.51 mg/m^3 for the mean, and 9.95 and 10.81 mg/m^3 for the standard deviation, respectively. Hence, these two variables have similar values and similar data dispersion for this group. For the hypertrophic group, the in-situ data and C2RCC variables also have similar values, with a mean of 62.13 and 69.96 mg/m^3, respectively, and a standard deviation of 64.57 and 70.50 mg/m^3.

In contrast, the variables C2X and C2XC have significantly higher values and much greater data dispersion for both groups. With values above 100, reaching 1994.48 mg/m^3 for the hypertrophic waters standard deviation analyzed with C2XC. The enormous scatter of data in the C2X and C2XC variables ultimately indicate the unsuitability of the model applied.

Previously mentioned characteristics of the distribution of data in the different methods are shown in Fig. 6, where it can be seen a deviation in the mean of C2X and C2XC which is overestimated with respect to in-situ data, and also a larger variability. In spite of this result, C2RCC shows a quite accurate approach to in-situ data, both in mean and in variability.

Aiming to cover the total data set, the RMSE and MAAE have been found for all the samples. Table 5 shows how AC derived products find extremely high chlorophyll-a values. For the whole dataset, it can be observed that the C2RCC model performs better than

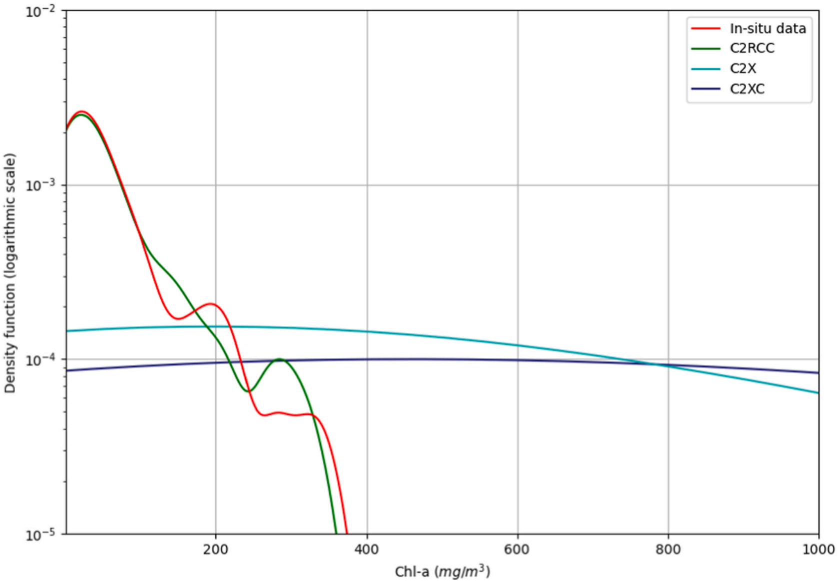

Fig. 5. Kernel density estimation of Chl-a concentration according to each measurement method.

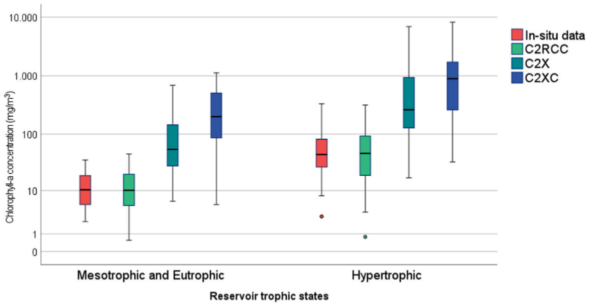

Fig. 6. Boxplot for Chl-a concentration (mg/m^3) for both water types and measuring methods. Ordinate axis is shown in logarithmic scale.

Table 4
Descriptive statistic for both water types and measuring methods. Data are shown in mg/m^3.

	Mesotrophic and Eutrophic		Hypertrophic	
	Mean	Standard deviation	Mean	Standard deviation
In-situ data	13.26	9.95	62.13	64.57
C2RCC	13.51	10.81	69.96	70.50
C2X	116.70	153.28	909.17	1456.60
C2XC	311.56	285.14	1597.55	1994.48

Table 5
Root Mean Square Error and Mean Absolute Average Error for each AC processor. Data are shown in mg/m^3.

All data		C2RCC	C2X	C2XC
	RMSE	30.73	1325.42	2007.70
	MAAE	17.54	590.34	1110.43
Meso. and Eutrophic	RMSE	7.13	178.97	405.07
	MAAE	4.79	103.94	298.80
Hypertrophic	RMSE	37.49	1626.93	2454.92
	MAAE	24.12	843.30	1530.05

the C2X and C2XC algorithms in all categories, with lower RMSE and MAAE values. It is noted that the C2RCC AC performance features a 7.13 mg/m^3 RMSE for mesotrophic and eutrophic water bodies, with a 4.79 mg/m^3 MAAE. In the hypertrophic category, the C2RCC model is still the best, although the RMSE and MAAE values are unsuitable for all AC, with extreme errors for C2X and C2XC.

In Fig. 7, the Kernel Distribution Estimation is shown mesotrophic reservoirs are represented in yellow, eutrophic reservoirs are shown in teal and hypertrophic reservoirs are shown in blue. Along with Table 6, the C2RCC AC, in addition to showing the best values, also shows the highest Spearman correlation coefficients. The linear correlation between the in-situ values and the remote sensing data is shown in Fig. 8, where blue dashed line represents 1:1 relation between x and y variables, so every point below the line is an overestimated value with respect to in-situ data; every point above the line is an underestimated value. It can be seen that both

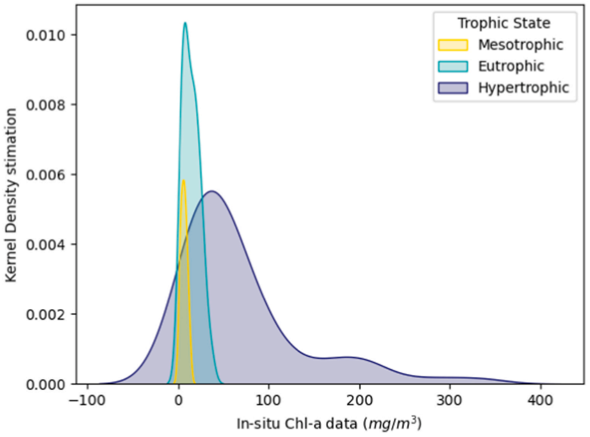

Fig. 7. Kernel Density Estimation of distribution function for Chl-a in-situ data.

Table 6
Spearman correlation coefficients for all water types considered.

	AC	Spearman Correlation
All values	C2RCC	0.88
	C2X	0.82
	C2XC	0.84
Meso. and Eutrophic	C2RCC	0.85
	C2X	0.80
	C2XC	0.84
Hypertrophic	C2RCC	0.83
	C2X	0.77
	C2XC	0.82

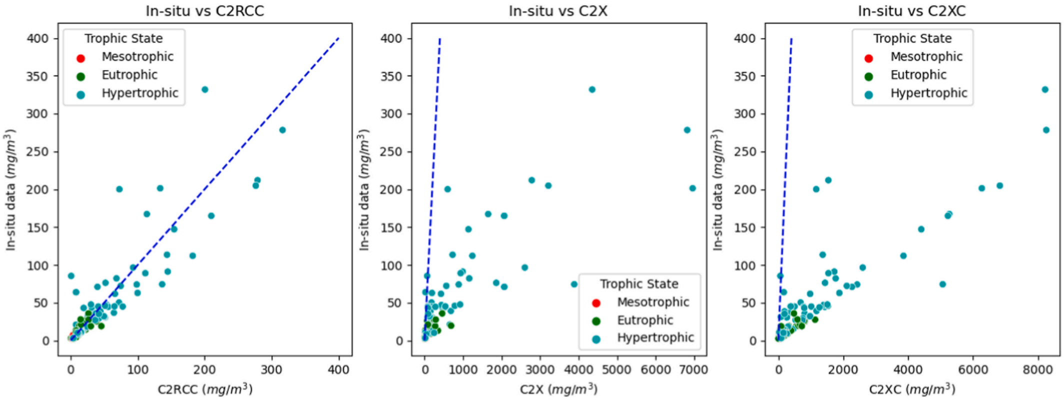

Fig. 8. Scatter plot for all reservoir types and AC.

C2X and C2XC tend to overestimate Chl-a concentration, especially for high values of the variable, although the latter show a lower scatter.

These data, together with the errors present in Table 5, show that there is a strong statistical relationship between the sets, but the models are inaccurate, with a positive error, hence the applied methodology has shown to find values far from the measurements in the case of C2X and C2XC. However, the C2RCC values, considering that the highest value from the 90 m buffer has been chosen, are much more accurate, with a total correlation of 0.88 and a RMSE of 7.13 mg/m^3 for the mesotrophic and eutrophic reservoirs. Coefficients coincide with correlations found in Delegido et al. (2014), a similar statistical study conducted over a heterogenous dataset including values from Rosarito reservoir, near Extremadura, Spain. Also, Chl-a RMSE were found to be 19 mg/m^3 for the Spanish lagoon Albufera de Valencia.

The work developed coincides with previous research, in which good correlations with C2RCC have been found (Pereira-Sandoval et al., 2019), that stated the processor's applicability over Spanish inland water masses in the east of the country. According to the authors, results can be improved considering aerosol data, which might also apply to the present study. However, shape and size are also mentioned to be a possible cause for results variability. Indeed, we consider our study area to be challenging in the referred terms, and further studies could benefit from spatial features categorizations. When compared among six atmospheric corrections, Warren et al. (2019) also found the best absolute results for the C2RCC algorithm, applied over four different European zones including the Spanish coast of Galicia.

Regarding C2X and C2XC, Soriano-González et al. have also pointed out their constraints depending on the water bodies analyzed (Soriano-González et al., 2022), which may need to be combined with other methods for its improvement. According to the author, C2-Net derived Chlorophyll-a concentration values can benefit from further recalibrations, as the site specifications do not fit the studied Spanish reservoirs characteristics. Compared to the Spanish coastal lagoon Mar Menor, the findings differ from those of Zhan et al. (2022). These differences might arise from other bio-chemical parameters, such as turbidity (Delegido et al., 2019).

In any case, the errors found for mesotrophic and eutrophic reservoirs are similar to those found in (Ogashawara et al., 2021), a study that also classified these trophic states, while finding poor results for oligotrophic reservoirs. Other negative statistics have been found by C2-Net algorithms, such as those applied in Sentinel 3 in (Alcântara et al., 2018) or Sentinel 2 (Ansper and Alikas, 2019). The latter study refers to issues such as the shape of the reservoir and its influence on adjacency or distribution effects. Based on these findings, we consider that this may be one of the main reasons for the results found in our study. The calibration of the algorithms applied in water bodies different from those of Extremadura may be a cause of the results of the analysis. This hypothesis coincides with the conclusions of Niroumandi et al. (Niroumand-Jadidi et al., 2021) who estimated that a global calibration of the C2-Net method with the established IOPs is not sufficient for the determination of parameters in other lakes with specific characteristics. These features could be common for the Italian and Spanish lakes analyzed in the mentioned studies. Such an analysis would require a comparison of other parameters (turbidity, CDOM, TSM ...). A further possible limitation is the analysis of a wide range of data; the analysis applied according to a division of more water types, deepening the methodology of this research, can be a solution to obtain good algorithms for the extraction of variables, as has been demonstrated in other studies (Sòria-Perpinyà et al., 2022)– (Soomets et al., 2020).

4. Conclusion

This research study has analyzed the chlorophyll-a retrieval performance of C2-Net algorithms over ninety-four water samples from thirty-two small reservoirs in the Spanish region of Extremadura. We summarize the main conclusions in the following points:

- In the comparison between the different Chl-a automatic products of different C2-Net methods, the best results were obtained with the C2RCC algorithm, while the C2X and C2XC algorithms proved to be inappropriate for the methodology applied. This might be due to the differences between the training dataset used in the method development and the specimens used in this work.
- The C2RCC algorithm has shown the lowest errors in mesotrophic and eutrophic waters, with a considerably better performance than in hypertrophic reservoirs.
- In general, extraction of chlorophyll-a values by atmospheric corrections shows higher accuracy in reservoirs with mesotrophic and eutrophic trophic states below 25 mg/m^3.
- Given the good correlation between C2X and C2XC with in-situ data, although monotonically overestimating the Chl-a in-situ concentration, a line of future research should be to correct C2X and C2XC values according to the size of the inland mass to take into account the different reflectance values in these masses.

The authors believe that remote sensing is a suitable tool for the study of the trophic state in the small mesotrophic to eutrophic reservoirs of the region, with good results drawn from the C2RCC algorithm. Future research on the area shall focus on improving C2-Net methods by analyzing the sensitivity of different extraction windows and statistical values used for chlorophyll-a value extraction. Also, a larger set of training data could be provided for the improvement of the method. Furthermore, the study of small reservoirs can be reinforced with a larger number of samples and reservoirs in the studied region, considering the qualitative and quantitative importance of existing reservoirs.

Ethical statement

Hereby, I José Cáceres-Merino consciously assure that for the manuscript *An application of C2-Net Atmospheric Corrections for Chlorophyll-a estimation in small reservoirs* is fulfilled:

1) This material is the authors' own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in prior and existing research context.
6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
7) All authors have been personally and actively involved in substantial work leading to the paper and will take public responsibility for its content.

Credit author statement

Aurora Cuartero: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Writing – Original Draft, Writing – Review and Editing, Supervision, Project Administration, Funding acquisition.

José Cáceres-Merino: Formal analysis, Investigation, Resources, Data curation, Writing – Original Draft, Writing – Review and Editing, Visualization.

Jesús A. Torrecilla-Pinero: Software, Validation, Formal Analysis, Investigation, Data curation, Writing – Review and Editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Aurora Cuartero reports financial support was provided by Government of Extremadura Education and Employment Department.

Data availability

Data will be made available on request.

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