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Water Transparency in a Shallow Eutrophic Lagoon (Albufera of Valencia, Spain) Using Sentinel-2 Images †

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Abstract: This study develops a novel algorithm utilizing Sentinel-2 imagery to estimate Secchi disk depth, a vital indicator of water clarity in the eutrophic Albufera de Valencia. Among three models tested, R560/R705 demonstrated superior performance, achieving R2 values of 0.6149 (calibration) and 0.916 (validation). This algorithm significantly enhances depth estimation accuracy (NRMSE reduced from 20.7% to 17.8%) compared to previous models. It offers a precise tool for monitoring water clarity in this ecologically vital lagoon, crucial for its natural and cultural significance.

Keywords: Secchi disk depth; water quality; eutrophication

1. Introduction

Water clarity, fundamental to assessing water quality, refers to transparency and turbidity [1]. It is conventionally quantified by the Secchi Disk Depth (Z_{SD}), the vertical distance until the disk is no longer visible [2,3]. This parameter indicates the depth at which sunlight penetrates the water [4].

Increased phytoplankton and sediments due to eutrophication reduce light penetration, affecting biological processes [5,6]. Thus, Z_{SD} is inversely linked to inorganic and organic material in water [7]. Since the 1970s, the introduction of nutrients has led to eutrophication processes in the Albufera lagoon. This has resulted in a marked degradation of the wetland area [8]. Chlorophyll-a concentration, Z_{SD} and concentrations of total phosphorus and total nitrogen reflect this transformation [9].

In this context, the main objective of this study is to develop an improved algorithm to estimate the Z_{SD} in the Albufera lagoon. The selection of the Albufera as a study area is based on these circumstances, highlighting the importance of understanding the specific characteristics of water bodies when developing algorithms to estimate water quality parameters. Remote sensing emerges as a crucial tool for monitoring and managing water resources in complex aquatic environments [10]. This will contribute to sustainable water management and aquatic ecosystem conservation in the context of climate change, in line with SDG 6 [11].

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2. Materials and Methods

During July and August 2018, July 2021, November 2021, in the period between March and December 2022 and between February and May 2023, weekly sampling was carried out in the Albufera de Valencia lagoon. On days with good weather, boat trips were carried out to obtain samples at four specific points: "North", "Center", "South" and "Quay" (Figure 1). Occasionally, other points such as P1 and P2 were sampled, depending on sampling interests.

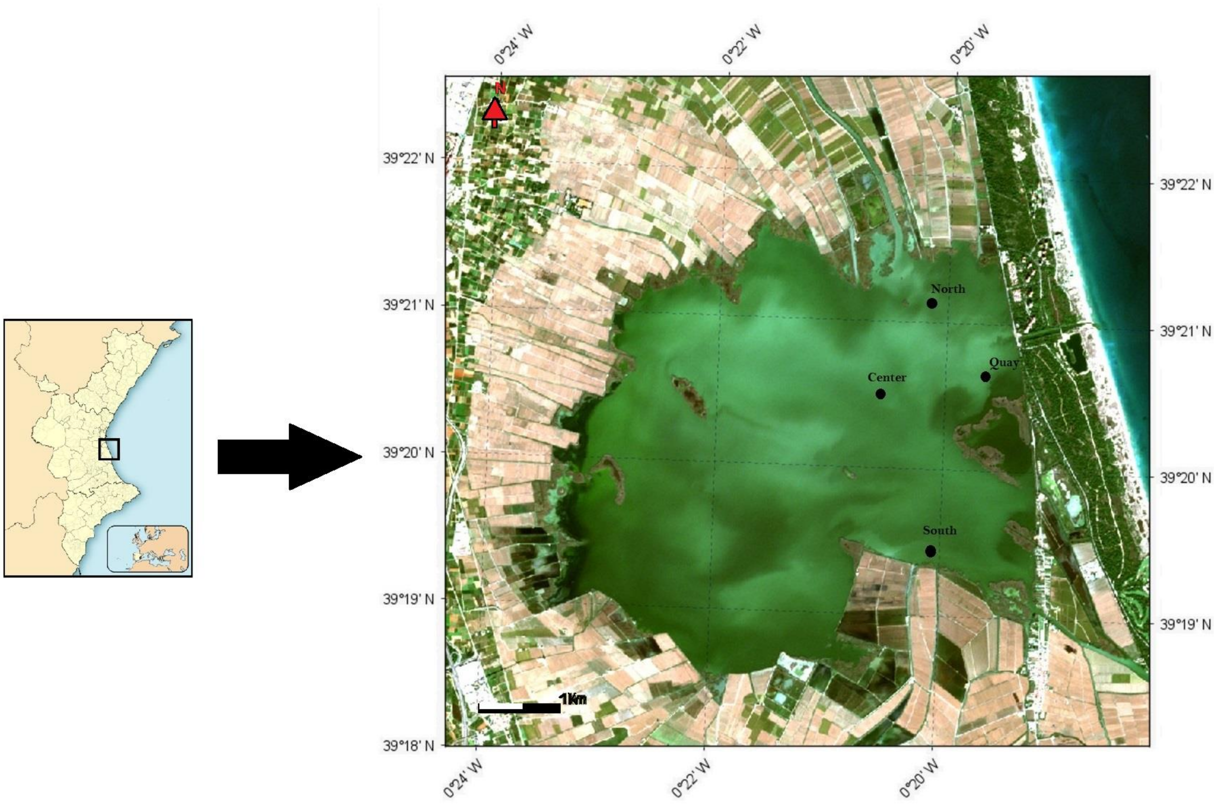

Figure 1. Location of field sampling points in the Albufera lagoon. Date of image from Sentinel-2: 01-nov-2022.

These samplings were scheduled close to the acquisition of images by the S2A satellite, following Kutser [12]. Water transparency [13], temperature and conductivity were measured, and samples were taken to calculate [Chl-a] in the laboratory. Chlorophyll was extracted from the filtered samples using a solution prepared with dimethyl sulfoxide and 90% acetone following the method of Shoaf and Lium [14]. Chl-a] was determined using the calculation methodology of Jeffrey and Humphrey [15].

Subsequently, remote sensing images from the ESA Sentinel-2 mission were processed. Twenty-one cloud-free images corresponding to the field data in the lagoon and atmospherically corrected with Sen2Cor (level 2A), known to provide optimal reflective results in eutrophic waters [16,17], were carefully selected. The images were resampled to a spatial resolution of 10 meters and the reflectivity of the first 7 spectral bands was calculated from a 3x3 pixel grid corresponding to each sampling point and date [12].

To calibrate the algorithms, optical models were selected from the literature based on how solar radiation reflects off the water surface as a function of the substances present (Table 1). These models must consider differential scattering and reflection of light by phytoplankton, suspended inorganic material, and dissolved organic matter [18].

Table 2. Proposed index for estimating Secchi disk depth (Z_{SD}) in Albufera of Valencia.

Model	References
R490/R560	Mueller [19] and Giardino et al. [20]. Used by Delegido et al. [21] in reservoirs of the Jucar basin.
R490/R705	Originally Alikas and Kratzer [22]. Employed by Pereira-Sandoval et al. [23] in the Albufera of Valencia and reservoirs of the Jucar basin.
R560/R705	Originally Koponen et al. [18]. Sòria-Perpinyà et al. [16] in the Albufera of Valencia.

In the case of the blue band (R490), the main phenomenon is the reflectivity of water, which decreases with the presence of suspended material [24]. The green band (R560) shows minimal absorption of the combination of photosynthetic pigments [25], suspended particles and dissolved organic material [26]. In the red band (R705), [Chl-a] shows a reflectivity peak at 700 nm, which will be higher the higher its concentration, related to light scattering and absorption by phytoplankton [27] and its maximum fluorescence at 683 nm [28]. However, the impact of pigments is minimal at 705 nm, where the main phenomenon is backscattering caused by phytoplankton [25]. This is also influenced by near-infrared scattering originating from suspended particles, although water absorption continues in this wavelength band [12].

A linear regression analysis was performed to select the best-fit algorithm. The validity of the algorithm was evaluated by a new linear regression and the RMSE and NRMSE were calculated. Selected algorithm was applied to all images and Z_{SD} thematic maps were generated.

3. Results

3.1. Field and Laboratory Data

The descriptive statistics of the results obtained for the variables measured in the field and in the laboratory are presented in Table 2.

Table 2. Descriptive statistics of the variables measured in the study.

Variable	Average	Maximum	Minimum	Std. Dev.
Temperature (°C)	23.3	30.3	11.5	5.8
Conductivity (µS/cm)	1870.4	3040.0	1031.0	574.6
Secchi disk depth (m)	0.31	0.55	0.15	0.09
Chlorophyl-a (mg/m^3)	164.3	376.0	21.0	88.5

3.2. Algorithm Retrieval and Validation

Table 3 shows the equations derived during the calibration of the selected models for Z_{SD}. We have chosen the algorithm with the best correlation with field data, which obtained a p-value < 0.001.

Table 3. Results of the calibration of the algorithms for the estimation of the Secchi disk depth in the Albufera and comparative statistics of the validation of the algorithms selected in the present study and the previous study. The selected index with a higher coefficient of determination is indicated with (*). The algorithm developed in the previous study is identified with reference [16].

Algorithm	Calibration R^2	Validation R^2	RMSE	NRMSE
Z_{SD} = 0.4242 × R560/R705 + 0.0577 (*)	0.6149	0.916	0.07 m	17.8%
Z_{SD} = 0.224 × R560/R705 + 0.0836 [16]	Not calibrated in this study		0.08 m	20.7%
Z_{SD} = 0.3944 × R490/R705 + 0.1246	0.2805	Not selected	Not selected	Not selected
Z_{SD} = -0.0455 × R490/R560 + 0.3426	0.0043	Not selected	Not selected	Not selected

3.3. Thematic Maps

In Figure 2 we have a series of thematic maps showing spatial and temporal variability of water transparency during 2022. The maps demonstrate a seasonal temporal pattern, influenced by the rice fields cycle, which is related to the amount of organic matter present in the water, and the chlorophyll-a concentration. The moments of a major water transparency are winter and the final part of summer, while the opposite situation is detected in spring and autumn.

In terms of spatial variability, the study reveals significant disparities in water transparency between field-sampled points and satellite-derived averages. Thematic maps highlight this variation, showing lower transparency near the sampling points and higher levels along the western and southern coasts. This highlights the spatial complexity of transparency in the lagoon.

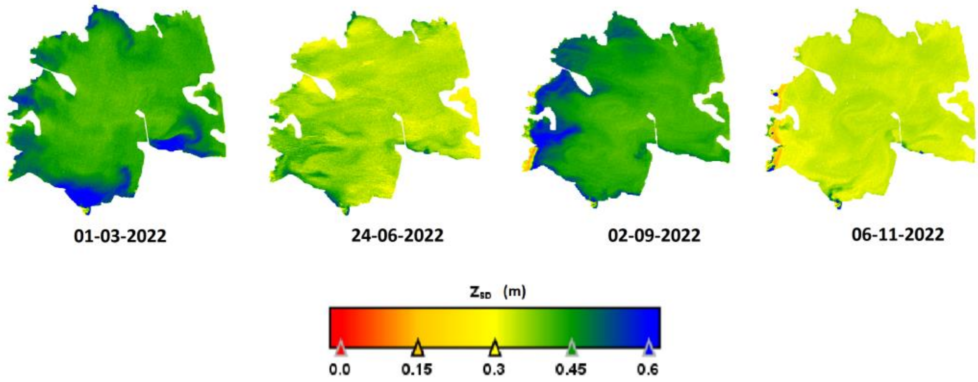

Figure 2. Thematic maps of Z_{SD} in different moments of 2022. Images obtained of Sentinel-2 and processed using SNAP 8.0.

4. Discussion and Conclusions

The study highlights the inadequacy of the R490/R560 [19–21] and R490/R705 [22,23] models for estimating Secchi disk depth (Z_{SD}) in the Albufera lagoon. These models, designed for very different aquatic environments in terms of transparency, fail to provide accurate results in this highly eutrophic lagoon.

The R560/R705 model, previously calibrated for turbid lakes in Finland [18], shows more promising results, agreeing with previous studies. The choice of this model is based on the trophic similarity of the Albufera lagoon with some of the lakes where the original calibration was performed. The use of the 560 nm band in this model is beneficial, since it presents a minimum light absorbance by pigments, dissolved organic matter and suspended solids.

The study also reveals a reduction in statistical error in the estimates compared to a previous algorithm [16]. This improvement can be attributed to both the increased amount of data and a slight decrease in water transparency during the period studied. This underscores the need for continuous updates in Z_{SD} estimation.

For future research, it is suggested to expand the data set for the development of an even better algorithm for the estimation of transparency in the Albufera lagoon. This is particularly important in the context of a trend towards further eutrophication of the system. Furthermore, it will be crucial to corroborate the differences in transparency between different areas of the lagoon.

Finally, the importance of remote sensing as a tool for the comprehensive assessment of aquatic ecosystems is underscored. Its ability to collect continuous and wide-ranging data over time allowed us to capture subtle variations in the Z_{SD} and correlate them with the evolution of the lagoon's state. This comprehensive approach improves our understanding of seasonal and spatial trends, providing crucial information for environmental monitoring and effective management of natural areas.

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