DECADAL LIMNOLOGICAL TRENDS AND EVIDENCE OF TROPHIC STATUS IN THE ALTO RABAGÃO AND AGUIEIRA RESERVOIRS (2014–2024)

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INTRODUCTION

1 Anthropogenic pressure and climate change
- Population growth
- Agriculture
- Industry
- Energy production
- Urban water suppy

2 Water resource stress
- Increased water demand
- Reduced water availability
- Altered precipitation regimes
- Higher evaporation rates

3 Water quality
- Nutrient enrichment
- Organic matter inputs
- Turbidity increase
- Transparency reduction

4 Ecological impacts
- Eutrophication
- Phytoplankton blooms
- Ecosystem imbalance
- Reduce water usability

5 Monitoring challenges
- Sparse field campaigns
- High operational costs
- Limited spatial coverage
- Low temporal resolution

6 Remote sensing with Sentinel- 2 (S2)
- Level- 2A reflectance
- 10 m spatial resolution
- 5 days revisit time
- Large-area coverage

7 Study objective
- chlorophyll a (Chl-a) estimation
- Secchi depth (SD) estimation
- Spatial distribution mapping
- Reservoir management support

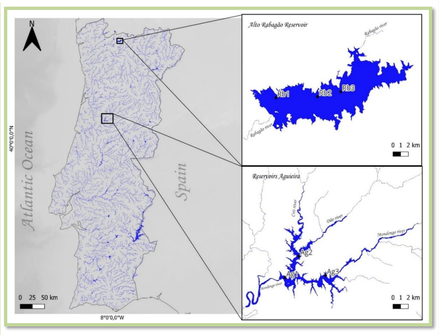


Figure 1. Location of the study areas and sampling sites in the Rabagão reservoir and in the Aguieira reservoir.

MATERIALS AND METHODS

1 Study areas

Rb
22.12km²
568.7km³

Ag
20 km²

2 Data sources

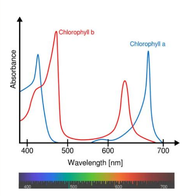
APA/SNIRH
Bi-monthly monitoring (2014-2024)

Seasonal field campaigns (2023-2024)

3 S2 acquisition and processing
- S2 level-2A Image selection
- ±3 days from field sampling
- Cloud cover < 30 %
- No atmospheric artefacts

ROI = 0.008Km² (80 pixels at 10 m resolution).
- Mean band reflectance extracted

4 Spectral index
- Three-band index (TBDO) R740(1/R665-1/R705) Dall'Olmo
- TBDO1, R665(1/R560-1/R443)
- Chlorophyll Index (MCI)
- Normalized Difference Index (NDI)
- simple band ratios (SR)



5 Modelling and validation

Multiple linear regression

Walk-Forward Time-series Cross-validation

Statistical comparison (t-test/Wilcoxon test)

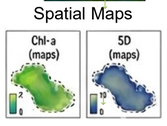
6 Spatial distribution mapping

Validated model implementation (Copernicus browser – evalscript)

NWDI water mask

Pixel-wise prediction

Spatial Maps



RESULTS AND DISCUSSION

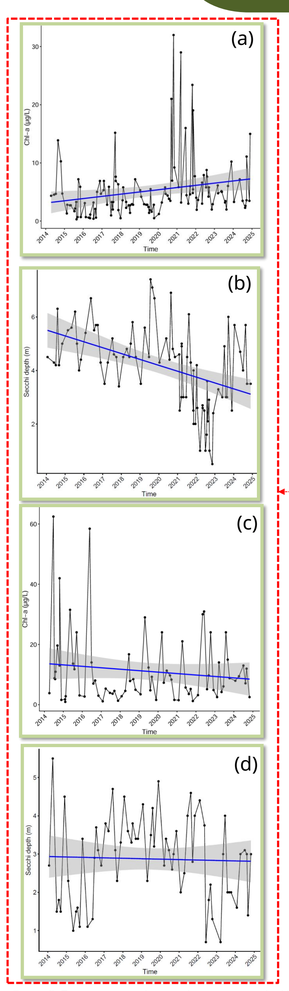


Figure 2. Temporal evolution and interannual variability of chlorophyll-a (a, c), box plots, µg L^{-1}), Secchi disk depth (b, d), in the Rb and Ag reservoir, respectively, from 2014 to 2024. Panels (a) and (c) include linear regression fit with 95% confidence interval.

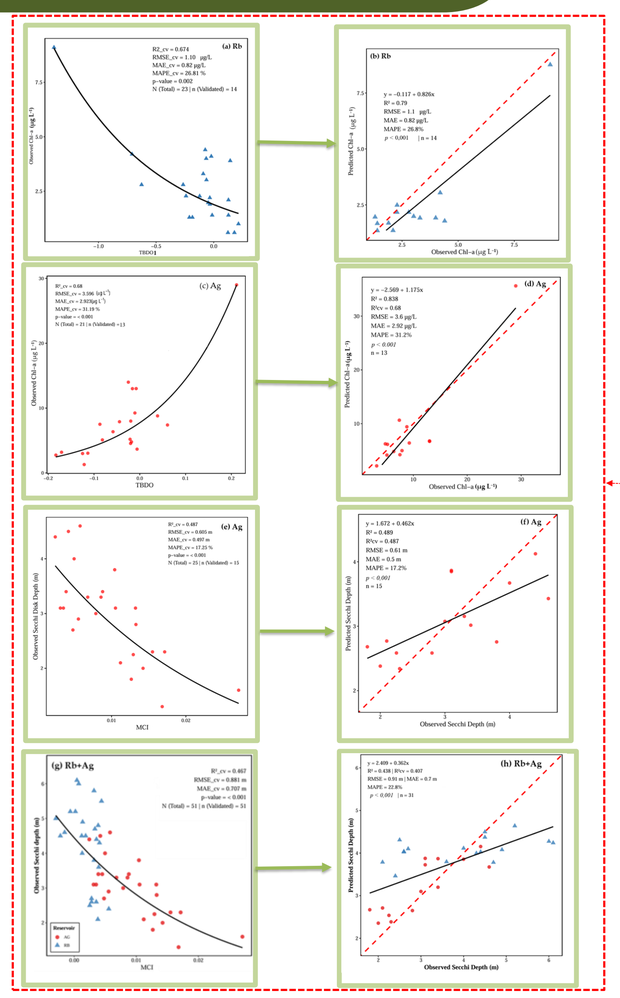


Figure 3. Observed *versus* predicted values of Chl-a and SD based on the best validated empirical models (time-series cross-validation). Panels show: (a) Chl-a vs TBDO1 in Rb; (c) Chl-a vs TBDO in Ag; (e) SD vs MCI in Ag; and (g) SD vs MCI using combined data from both reservoirs. The respective validation panels (on the right) are shown in (b, d, f, h). In the validation panels (right column), the solid black line represents the fitted linear regression, and the dashed red line indicates the 1:1 relationship between observed and predicted values.

Water Quality Trends
- **Rb:** ↑ Chl-a and ↓ water transparency over time.
- **Ag:** stable conditions despite high productivity.

Remote Sensing Performance
- Sentinel-2 successfully estimated Chl-a and SD.
- Reservoir-specific models outperformed combined models.

RESULTS AND DISCUSSION

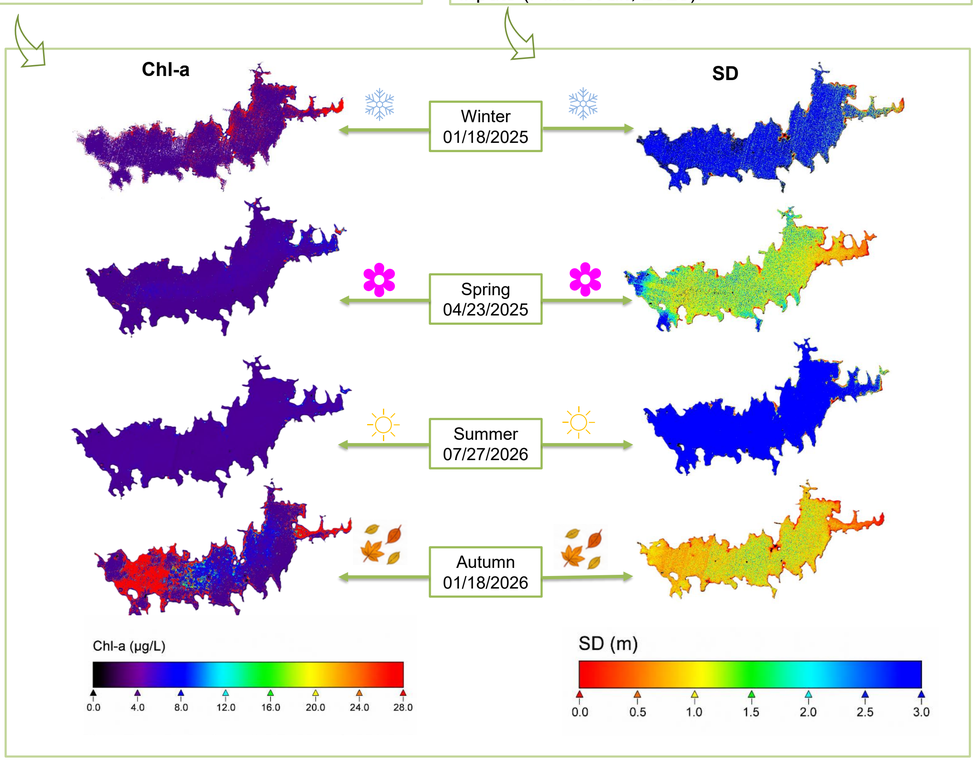
Differences between reservoirs
- **Ag** showed higher model accuracy due to stronger phytoplankton dominance, as presented Matthews (2011) and Sòria-Perpinyà *et al.* (2018).
- **Rb** presented more complex optical conditions due to its low phytoplankton concentration

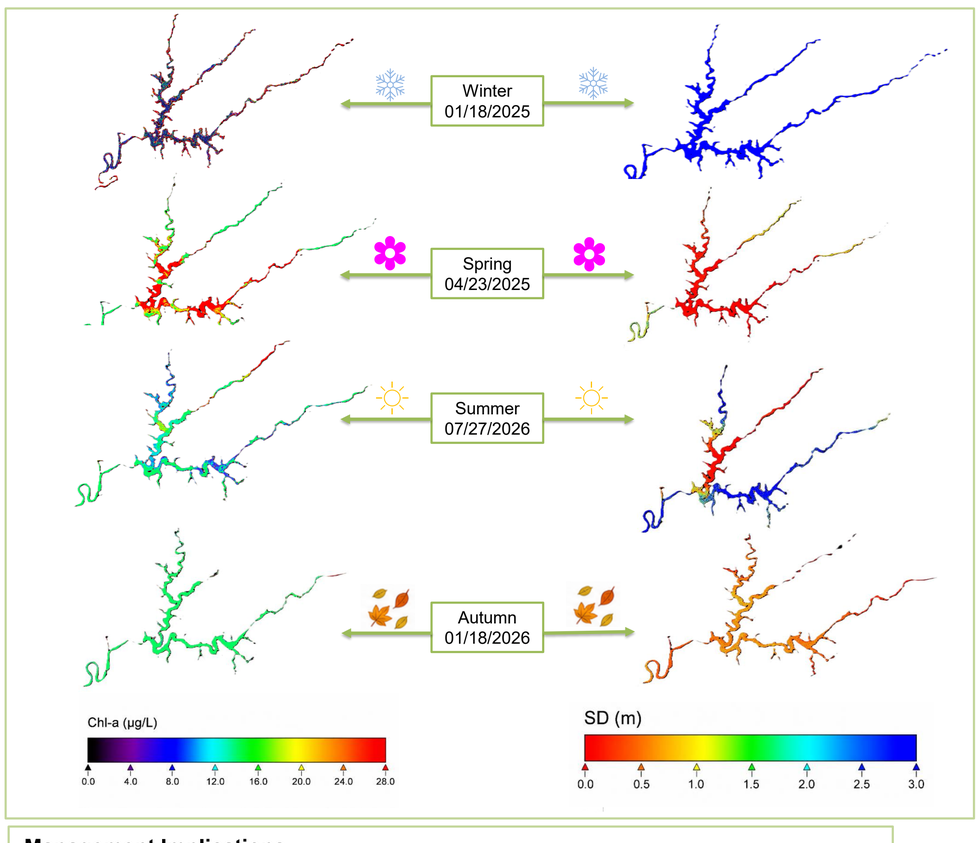
Table 1. Time-series cross-validation performance of empirical models for estimating limnological parameters using Sentinel-2 data. *Best models.

		Model	R^2_{cv}	RMSE	MAE	MAPE(%)	*p*-value	n_{cv}
Best models	Rb	$Chl-a(\mu gL^{-1}) = 1{,}888 \cdot e^{(-1{,}1323 \cdot TDBO1)}$	0.67*	1.10	0.82	26.8	*p*=0,002	14
		$SD(m) = 5{,}568 - 3{,}542 \cdot NDI$	0.26	1.29	1.07	44.4	*p*<0,001	15
	Ag	$Chl-a(\mu gL^{-1}) = 7{,}745 \cdot e^{(6{,}2408 \cdot TBDO)}$	0.68*	3.60	2.92	31.2	*p*<0,001	13
		$SD(m) = 4{,}295 \cdot e^{(-42{,}467 \cdot MCI)}$	0.49*	0.61	0.50	17.2	*p*<0,001	15
	Rb+Ag	$\mathrm{Chl-a(\mu gL^{-1})} = 2{,}466 \cdot e^{(-0{,}9194 \cdot TBDO1)}$	0.37	4.22	2.34	47.1	*p*<0,001	36
		$SD(m) = 4{,}446 \cdot e^{(-45{,}8029 \cdot MCI)}$	0.45*	0.89	0.71	23.7	*p*<0,001	46

Spatiotemporal Dynamics
- Water quality patterns varied with rainfall and hydrological conditions.
- Spatial heterogeneity increased during runoff events.

Watershed Influence
- **Rb:** lower anthropogenic pressure and better ecological status.
- **Ag:** higher human pressure and greater nutrient inputs (Pinto *et al.*, 2025).





Management Implications
- Early signs of eutrophication detected in Rb.
- Sentinel-2 supports cost-effective long-term monitoring in this study, as well as in the study by Chen *et al.* (2022).
- Remote sensing can complement WFD monitoring programs.

CONCLUSIONS

- The **integration of *in situ* data with Sentinel-2 L2A is effective and scalable**.
- It is important to highlight the need for **model calibration for each specific location**.
- Despite **the fact that Rb is an oligotrophic reservoir**, it showed an increase in Chl-a concentration and a decrease in transparency.
- The **Ag** reservoir did not show significant long-term trends in Chl-a or SD, maintaining its Moderate to Poor status.

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Project 2Qua (Water Quality and Quantity, the challenge for the present and future) is supported by European funds, through COMPETE2030, and national funds, through the Portuguese Foundation for Science and Technology. *Operation nr. 15807 | COMPETE2030-FEDER-00691600 (https://doi.org/10.54499/2023.17517.ICDT)*