Seasonal Variability of Chlorophyll in Lake Cuitzeo, México with Hyperspectral EnMAP Data

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Abstract

Lake Cuitzeo, Mexico's second-largest freshwater lake, is a highly eutrophic system with spatial and seasonal variability. Monitoring chlorophyll-a, a key indicator of phytoplankton biomass and trophic status, is essential for understanding its ecological dynamics and supporting surrounding communities reliant on the lake's resources. This study employed hyperspectral EnMAP imagery acquired during the dry (April 2025) and wet (August 2025) seasons to assess chlorophyll-a distribution. Water pixels were delineated using the Modified Normalized Difference Water Index (MNDWI), while chlorophyll-a concentrations were estimated with the Normalized Difference Chlorophyll Index (NDCI), which is particularly effective in optically complex inland waters. Two in-situ chlorophyll-a measurements collected during the dry season were used for qualitative consistency verification. Although a two-sample t-test indicated no statistically significant difference in mean NDCI between seasons ($t = 1.27$, $p = 0.204$), spatial analysis revealed marked heterogeneity. Elevated NDCI values during the wet season were concentrated in the central–western basin, whereas higher dry-season values were observed along shallow eastern shorelines. These results underscore the value of high-resolution, spatially explicit monitoring for detecting localized eutrophication and guiding management strategies aimed at preserving the ecological and socio-economic functions of Lake Cuitzeo.

1. Introduction

Remote sensing techniques have been extensively employed over the past five decades across a range of sectors, including water quality assessment and monitoring. Their advantages—requiring less time and fewer resources than traditional field-based approaches—have been further strengthened in recent decades by the advent of hyperspectral sensors. These sensors provide high spectral resolution through narrow, contiguous bands across specific regions of the electromagnetic spectrum, enabling more precise discrimination of materials such as plant species, chlorophyll, contaminants, and other environmental indicators (Mishra et al., 2014). The capacity to detect subtle spectral differences renders hyperspectral remote sensing particularly effective for monitoring chlorophyll concentrations, a key proxy for phytoplankton biomass and primary productivity in aquatic ecosystems (Arias et al., 2025; Fabbretto et al., 2024).

In this context, chlorophyll monitoring is of particular importance for Lake Cuitzeo, where environmental conditions make the system highly vulnerable to rapid ecological change (Rodríguez-Gómez et al., 2025). The lake's shallow depth, elevated nutrient inputs from surrounding agricultural and urban areas, and pronounced seasonal fluctuations in water level contribute to the frequent occurrence of phytoplankton blooms (Moreno & Retana, 1995). These blooms are often associated with eutrophication, oxygen depletion, and harmful algal events, which can severely degrade water quality, disrupt biodiversity, and threaten the livelihoods of local communities (Bernal-Brooks et al., 2016).

Lake Cuitzeo, located within the states of Michoacán de Ocampo and Guanajuato (Figure 1), is also the most saline lake in Mexico and the second largest by surface area (Mendoza et al., 2011). It lies within a closed watershed of the Trans-Mexican Volcanic Belt at an average altitude of 1,850 m a.s.l., between latitudes 19° 30′ N and 20° 05′ N, and longitudes 100° 35′ W and 101° 30′ W, covering an area that fluctuates seasonally between 300 and 400 km² (Bravo Espinosa et al., 2008).

Figure 1. a) Red polygon signals east section of Lake Cuitzeo, b) Red rectangle signals its location within México.

2. Methodology

For this study, we utilized hyperspectral imagery from the Environmental Mapping and Analysis Program (EnMAP) (Guanter et al., 2015). Two acquisition dates were selected—23 April 2025 and 9 August 2025—representing contrasting seasonal conditions in terms of precipitation. April corresponds to the dry season, whereas August, particularly in 2025, followed a period of substantial rainfall, leading to markedly different hydrological and ecological conditions in the lake system.

The EnMAP sensor acquires contiguous spectral data across the visible to shortwave infrared range (420–2450 nm), distributed over 242 bands with an average spectral sampling of 6.5 nm. The data were obtained at Level-2A processing, which includes radiometric and geometric corrections, orthorectification based on a digital elevation model, and atmospheric correction for both terrestrial and aquatic targets using the EnMAP-Box processor (van der Linden et al., 2015). This level ensures surface reflectance products corrected for aerosol and water vapor effects, enabling reliable inter-date comparisons of spectral indices.

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Each Level-2A scene has a spatial resolution of 30 meters, projected in UTM Zone 14N (WGS84), and is delivered with all associated quality masks (e.g., cloud, cloud-shadow, and no-data flags). The combination of high spectral fidelity and calibrated surface reflectance allows for detailed analysis of bio-optical indicators such as the Normalized Difference Chlorophyll Index (NDCI) and the Modified Normalized Difference Water Index (MNDWI) employed in this work.

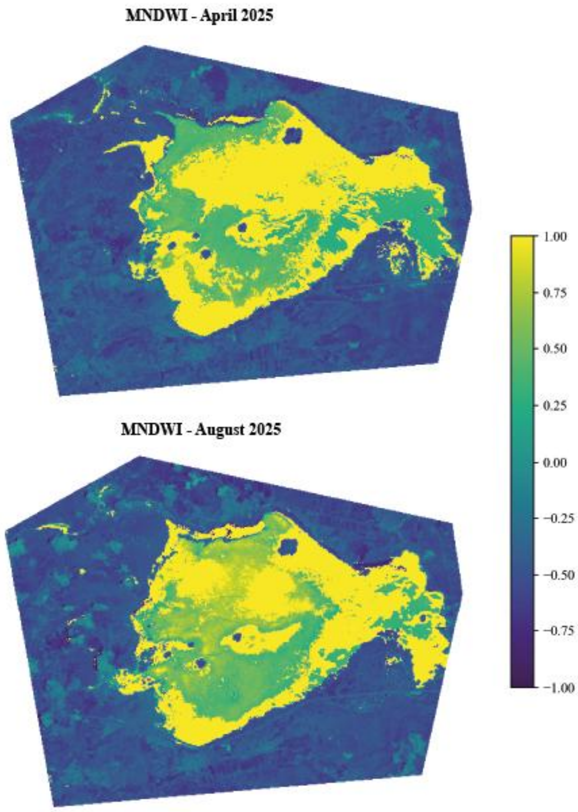

Figure 2. MNDWI values for dry (April) and wet (August) seasons over the eastern sector of Lake Cuitzeo.

The analysis focused on the eastern sector of Lake Cuitzeo (Figure 1), an area that generally maintains a relatively stable water level throughout the year. In contrast, the western portion of the lake experiences pronounced seasonal water loss, with some years witnessing the complete disappearance of its water reserves (e.g. 2023). Concentrating on the eastern section ensures consistency in water surface coverage across dates, thereby minimizing confounding effects due to significant variability in water extent. This sector also encompasses several long-term in situ monitoring stations (e.g. rainfall, humidity, etc), providing a reliable spatial reference for evaluating temporal changes in optical properties and validating remote-sensing estimates for many studies.

To isolate water pixels from other land cover types, the Modified Normalized Difference Water Index (MNDWI) was first applied (Equation 1), using a threshold value of 0.0, following established approaches in the literature (Huang et al., 2018; Xu, 2006) (Figure 2). This step ensured that subsequent chlorophyll analysis was restricted to open-water areas. The MNDWI was computed using the green (~550 nm – Band 39) and shortwave infrared (~1600 nm – Band 178) bands from EnMAP, taking advantage of the sensor's hyperspectral configuration to refine the discrimination of optically complex shallow-water zones. Applying this mask to the Level-2A scene to discriminate surface covered by water, reduced potential contamination from shoreline vegetation, sediment-laden shallow pixels, and mixed land–water edges, thereby improving the reliability of subsequent NDCI retrievals.

$$\mathrm{MNDWI} = \frac{R_{\mathrm{GREEN}} - R_{\mathrm{SWIR}}}{R_{\mathrm{GREEN}} + R_{\mathrm{SWIR}}} \tag{1}$$

Chlorophyll-a concentrations were then assessed using the Normalized Difference Chlorophyll Index (NDCI) (Equation 2). The NDCI utilizes reflectance values from the red (~665 nm – Band 56) and red-edge (~708 nm – Band 64), which capture key spectral features related to chlorophyll absorption and reflectance peaks (Mishra & Mishra, 2012). This index is widely recognized for its ability to detect and quantify variations in chlorophyll-a, particularly in turbid, eutrophic, or optically complex inland waters where traditional blue–green ratios often fail to perform reliably (Fendereski et al., 2024). The NDCI is a dimensionless reflectance-based index in which higher values correspond to increased chlorophyll-a concentrations and, consequently, to higher phytoplankton biomass (Augusto-Silva et al., 2014). Because chlorophyll-a acts as a proxy for primary productivity and trophic status, the NDCI provides an efficient and physically interpretable means of mapping spatial and temporal dynamics in lake productivity.

$$\mathrm{NDCI} = \frac{R_{708} - R_{665}}{R_{708} + R_{665}} \tag{2}$$

$$\Delta\mathrm{NDCI} = \mathrm{NDCI}_{wet} - \mathrm{NDCI}_{dry} \tag{3}$$

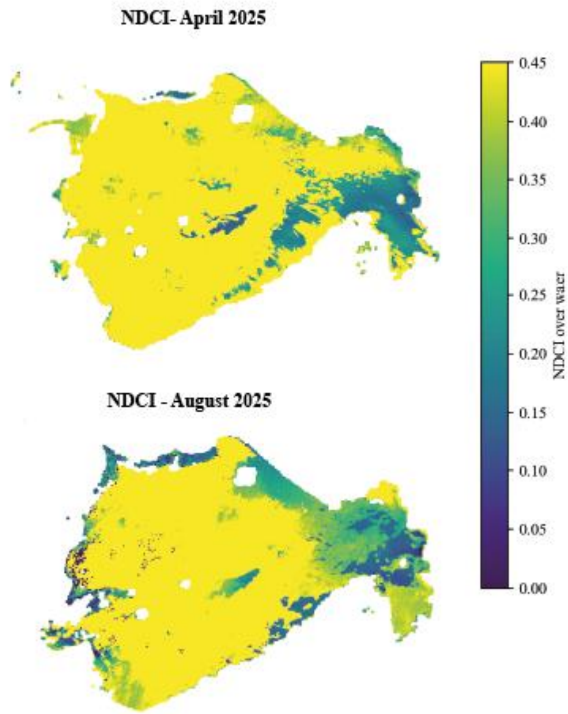

Figure 3. NDCI values for dry (April) and wet (August) seasons.

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Finally, the two seasonal NDCI maps (Figure 3) were compared by subtracting the dry-season values (April) from the wet-season values (August) (Equation 3). This pixel-wise subtraction produced a difference map (ΔNDCI), which highlights areas exhibiting either an increase or decrease in chlorophyll-a concentrations between the two acquisition dates (Figure 4). Positive ΔNDCI values indicate enhanced phytoplankton biomass during the wet season, whereas negative values suggest a decline or potential dilution effect due to increased water inflow.

To quantitatively assess whether seasonal variations in chlorophyll-a concentrations were statistically significant, a two-sample independent t-test was applied to the NDCI pixel distributions from the dry (April) and wet (August) seasons. The analysis considered only water pixels identified through the MNDWI-derived mask to avoid land contamination. The t-test was selected as it allows the comparison of two independent datasets with continuous variables (i.e. NDCI values) to determine whether their means differ beyond random variation (Lisboa et al., 2020; Wang et al., 2024).

To corroborate the satellite-derived chlorophyll-a estimates obtained from the NDCI, a qualitative comparison was performed using in situ measurements collected during the dry season. Chlorophyll-a concentrations were measured in-situ on 25 April 2025 with an YSI-EXO multiparameter probe, which quantifies fluorescence intensity in the spectral range of 470–685 nm, reported as Relative Fluorescence Units (RFU). Because RFU values are relative and can be affected by turbidity and other environmental factors, a calibration equation provided by the instrument was applied to convert RFU to chlorophyll-a concentration (μg/ L) (Equation 4).

$$\text{Chl-a } (\mu g/L) = (3.5 \times \text{RFU}) + 1 \quad (4)$$

This methodology as a whole provides a simple yet robust analysis for detecting overall differences in chlorophyll-related reflectance between seasons. Providing an objective measure of seasonal variation in chlorophyll-a concentration, facilitating the detection of spatially coherent patterns of productivity change within the eastern sector of Lake Cuitzeo.

3. Results

3.1 Seasonal chlorophyll-a distribution

The NDCI maps for April (dry season) and August (wet season) 2025 indicate that Lake Cuitzeo remains in a highly eutrophic state, with observable and quantifiable spatial variations in chlorophyll distribution between seasons (Figure 3). In April, high and relatively homogeneous NDCI values are widespread across the lake, whereas in August, slightly lower values and increased spatial variability are visible, particularly along the shorelines (Figure 3).

3.2 Seasonal chlorophyll difference

To highlight spatial changes between the two periods, the April (dry season) NDCI map was subtracted from the August (wet season) map (Equation 3), producing a difference map (ΔNDCI) (Figure 4). Positive ΔNDCI values indicate an increase in chlorophyll-a during the wet season, while negative values denote a decrease during the same season.

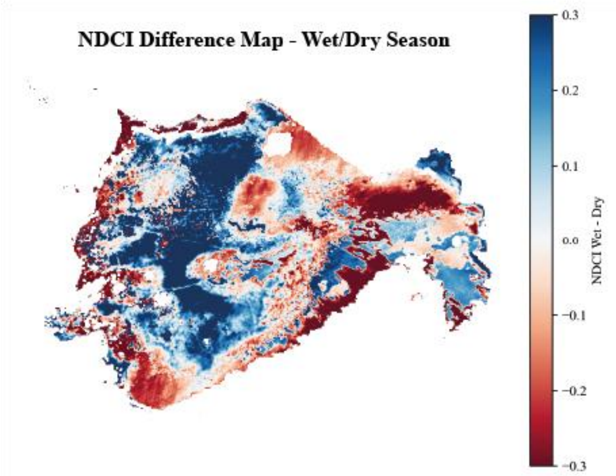

Figure 4. NDCI difference map, east section of Lake Cuitzeo.

The statistical comparison of NDCI values between the dry and wet season (April and August respectively) through a T-test, showed no significant difference in lake-wide mean chlorophyll-a concentrations. The resulting test statistics ($t = 1.27$, $p = 0.204$) indicate that, at the whole-lake scale, the mean chlorophyll-a concentration did not differ significantly between the two periods, although spatially heterogeneous changes are evident in the corresponding difference map (Figure 4), further discussed in Section 4.

3.3 In-situ chlorophyll-a measurements

To provide context for the satellite-derived estimates, in-situ chlorophyll-a measurements were collected during the dry season (April 25, 2025) using a YSI-EXO probe. Due to equipment delays, only two sampling sites (CTZ-E-05 and CTZ-E-06) successfully collected chlorophyll-a values from the eastern sector of the lake, for the dry season (April) (Figure 5).

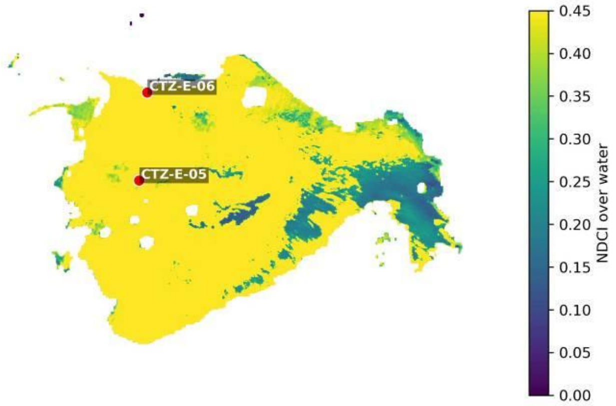

Figure 5. In-situ chlorophyll-a measurements on the eastern sector of Lake Cuitzeo, during the dry season (April 25th).

The measured chlorophyll-a concentrations of values between 6–9 μg/L, correspond to NDCI values of approximately 0.45 (Table 1), both consistent with eutrophic conditions (Figure 5). While the limited number of samples precludes statistical validation, the general agreement in magnitude supports the concordance of NDCI-derived estimates for representing high chlorophyll-a levels.

SITE	Chlorophyll (µg/L)	NDCI
CTZ-E-05	~6	~0.45
CTZ-E-06	~9	~0.46

Table 1. Chlorophyll-a values for in-situ measurements (µg/L) and NDCI derived values.

4. Discussion

As reported in previous studies, Lake Cuitzeo remains highly eutrophic throughout the year (Bernal-Brooks et al., 2016; Galindo de Obarrio, 2005). Although statistical comparison of NDCI values between the wet (August) and dry (April) seasons showed no significant difference in lake-wide mean chlorophyll-a concentration ($t = 1.27$, $p = 0.204$), the spatial analysis reveals seasonal heterogeneity in chlorophyll distribution.

During the dry season (April), elevated NDCI values (0.25–0.45) appear widespread across the lake, whereas during the wet season (August) slightly lower NDCI values and a greater spatial variability appear, particularly along the shorelines and in the central–western zones (Figure 3). This pattern suggests that increased precipitation and runoff may produce a dilution effect or enhanced mixing, which redistributes phytoplankton biomass more heterogeneously. Nevertheless, persistently high NDCI values near the west and shore-line areas suggest localized nutrient accumulation and shallow-water productivity that endure year-round.

The difference map (ΔNDCI = August minus April) reveals key spatial patterns (Figure 4). Zones where the wet season presents higher NDCI (shown by darker blue shades) are concentrated in the central–western basin. Such areas likely reflect increased nutrient input from tributaries during the wet season, combined with greater effective water depth and retention time, which can sustain phytoplankton growth despite inflow. Conversely, areas where the dry season shows higher NDCI (dark red shades) are primarily located along the shallow shorelines and in the eastern region. These shallow zones undergo more rapid warming, higher internal nutrient recycling and concentration of phytoplankton as water levels decline, conditions which are conducive to localized blooms and wind-driven shoreward concentration of biomass.

The histogram of ΔNDCI (Wet–Dry) values (Figure 6) complements the spatial analysis by quantifying the magnitude and direction of chlorophyll changes across the lake surface. The distribution is approximately symmetric but slightly skewed toward negative values, indicating that a larger portion of the lake experienced minor decreases in NDCI during the wet season. This pattern aligns with the visual evidence from the NDCI difference map (Figure 4), where extensive areas—particularly nearshore and in the eastern section—show reduced NDCI under wet conditions. The predominance of negative ΔNDCI values suggests that overall, phytoplankton biomass is slightly diluted or redistributed rather than enhanced during periods of higher inflow and mixing, existent in the rainy season.

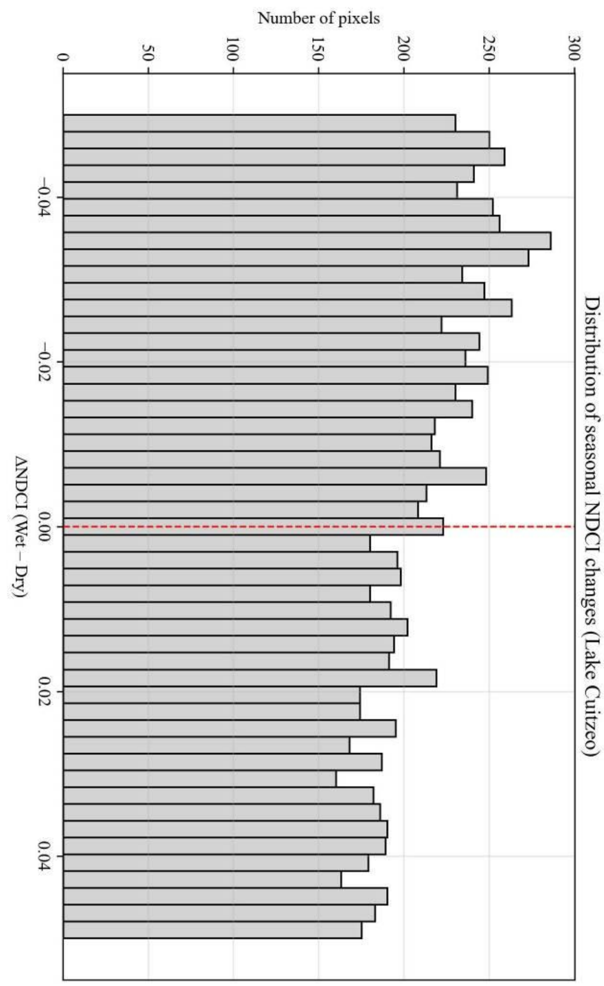

Figure 6. Distribution of seasonal NDCI difference map.

Nevertheless, the coexistence of localized positive ΔNDCI zones (blue areas in Figure 4) within the central–western basin demonstrates that nutrient enrichment and hydrodynamic retention can still sustain or even enhance productivity during the wet season. This spatial mosaic of contrasting responses underscores the lake's complex interplay between hydrology, nutrient dynamics, and geomorphology.

To deepen interpretation, three key drivers for these spatial patterns are expanded:

4.1 Depth variation and hydrology

Lake Cuitzeo is a shallow lake over all, with an average depth of 1m throughout the lake (Amador García et al., 2012). Regardless, shallower zones warm faster, stratify less, and offer a higher light environment and potentially greater internal nutrient recycling from sediments, all of which can enhance phytoplankton growth (Rogora et al., 2021). Meanwhile, deeper sections or sections with higher volume and flushing during the wet season may exhibit lower biomass unless nutrient input and retention support growth (Figure 7). The central–western basin of Lake Cuitzeo may combine its moderate depth (1-1.5 m) with increased water residence in the wet season, exhibited in higher NDCI values (Figure 4). By contrast, shore areas are more dynamic, shallow and subject to wind mixing and sediment resuspension, which may elevate biomass during the dry season.

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4.2 Watershed nutrient inflows

Seasonal run-off and tributary inputs deliver pulses of nitrogen, phosphorus and sediments which change the nutrient regime of the lake (Bhateria & Jain, 2016). During the wet season, increased flushing from the watershed may supply nutrients but also dilute biomass and increase turbidity, reducing light (Bernal-Brooks et al., 2016). The higher NDCI in the central–western basin during the wet season likely corresponds to zones receiving stronger inflow. Conversely, during the dry season, lower external inflow may allow internal nutrient recycling and stability of biomass along the shallower east shoreline areas. Studies that link satellite chlorophyll to upstream nutrient loads support this mechanism (Dietrich et al., 2024).

Figure 7. Photo taken in central western site CTZ-E-05, during the in-situ campaign in April 25th 2025.

4.3 Potential anthropogenic drivers

Agricultural and urban land use in the catchment contribute nutrient loads, sediment and organic matter which affect trophic state, light attenuation and nutrient cycling (Trueba Regalado & Paniagua, 2024). The spatial heterogeneity observed in NDCI may reflect zones with stronger anthropogenic influence (e.g., near inflow points draining farmland or urban zones) (Figure 8) and those less influenced (Fergus et al., 2016). Hence, management of land-based inputs remains a critical element for controlling eutrophication dynamics in Lake Cuitzeo.

Figure 8. Photo of cows eating algal blooms inside the lake during the in-situ campaign in April 25th 2025.

Overall, although no significant lake-wide difference in chlorophyll-a seasonally was observed, the spatial patterns uncovered by NDCI mapping reveal localized areas of intensified eutrophication in both the wet and dry periods. These findings underscore the importance of spatially explicit monitoring of chlorophyll-a, not only to understand phytoplankton dynamics but also to support the management of water quality for communities that rely on Lake Cuitzeo for farmland water, fisheries and agriculture, and to safeguard the ecological health and resilience of the lake ecosystem.

From a management perspective, the results emphasize that assessing eutrophication solely through seasonal averages risks overlooking significant sub-lake variability. Although the lake-wide mean chlorophyll concentration remains statistically stable between seasons, the spatial distribution of biomass shifts. Such heterogeneity can have ecological consequences, including local hypoxia, fish kills, or altered trophic interactions confined to specific zones (Arias et al., 2025; Dietrich et al., 2024).

Monitoring efforts should therefore integrate both temporal and spatial dimensions of chlorophyll-a dynamics. High-resolution remote sensing products from hyperspectral data, such as NDCI provide valuable tools to detect subtle intra-lake variations that are not captured by point-based measurements (Olivetti et al., 2023). Combined with hydrodynamic and nutrient input data, these spatial indicators can guide targeted management actions—such as prioritizing shoreline restoration or regulating inflows from agricultural subcatchments—to mitigate eutrophication in Lake Cuitzeo.

5. Limitations and future perspectives

While the results presented here provide valuable insights into the spatial dynamics of chlorophyll-a in Lake Cuitzeo, several limitations should be acknowledged. First, the analysis is based on two EnMAP acquisitions from a single year (2025), which constrains the temporal representativeness of the findings. Seasonal comparisons within a single hydrological cycle may not capture interannual variability associated with longer-term climatic fluctuations, lake-level dynamics, or land-use changes in the watershed. Incorporating multi-year datasets would allow a more robust assessment of recurring spatial patterns and the persistence of eutrophic conditions under different rainfall regimes.

Second, this study focused exclusively on chlorophyll-a as a proxy for primary productivity. Although NDCI effectively highlights phytoplankton biomass, complementary biological and optical variables (e.g. phycocyanin, total suspended matter, or dissolved organic carbon) would improve the ecological interpretation of trophic state and bloom composition (Villota-González et al., 2023). Furthermore, quantitative data on anthropogenic drivers, including agricultural runoff, wastewater discharge, and nutrient load estimates, would strengthen the causal understanding of spatial chlorophyll variability and support targeted management interventions.

Finally, ground-truth validation was limited by the availability of in-situ measurements, with only two stations providing reliable chlorophyll-a readings during the dry season. While these data supported the qualitative consistency of NDCI-derived estimates, a denser sampling network and repeated measurements across seasons would enhance statistical validation and facilitate the calibration of local bio-optical models. Expanding the integration of field data and hyperspectral imagery will be key to improving the accuracy, reproducibility, and applicability of satellite-based water quality assessments in Lake Cuitzeo and similar eutrophic lake systems.

6. Conclusions

This study highlights the potential of hyperspectral remote sensing, specifically EnMAP data, for assessing and monitoring chlorophyll-a dynamics in optically complex inland waters such as Lake Cuitzeo. Although statistical testing ($t = 1.27$, $p = 0.204$) indicated no significant difference in lake-wide mean chlorophyll-a concentrations between seasons, the NDCI difference map (Figure 4) and ΔNDCI histogram (Figure 6) revealed spatial heterogeneity, highlighting localized zones of both increased and decreased productivity. These patterns reflect the lake's sensitivity to seasonal hydrological changes, nutrient inflows, and internal recycling processes.

Beyond its application to Lake Cuitzeo, this work illustrates the relevance of spatially explicit analyses when assessing eutrophication and ecological health in shallow, dynamic lake systems. Integrating hyperspectral indices with hydrological and biogeochemical data can advance the understanding of trophic processes, enhance early detection of algal blooms, and support targeted management strategies aimed at mitigating nutrient pollution and preserving aquatic ecosystem resilience. Future work should focus on expanding the temporal record through multi-date EnMAP observations and incorporating additional field validation to refine empirical relationships for a broader model and the possibility of productivity predictions for Lake Cuitzeo.

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