

Mapping Aquatic Cyanobacterial Blooms Using Sentinel-2 Satellite Imagery [†]

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Abstract: Algal blooms are harmful and can hinder the use of water. Remote sensing satellite images can help monitor the spatial–temporal distribution of these blooms. This helps us understand their dynamics and manage them better. In our work, we developed an algorithm using Sentinel-2 images. The validated algorithm showed good accuracy, suggesting the potential use of Sentinel-2 images to monitor algal blooms in other water bodies.

Keywords: code 6S; bands; chlorophyll-a

1. Introduction

Lakes and reservoirs are valuable natural resources that offer essential ecological, environmental, and hydrological services [1–3]. Cyanobacterial blooms are a serious problem in freshwater bodies, often suffering from eutrophication and the mismanagement of watersheds [4]. They can produce lethal cyanotoxins that threaten human health and aquatic inhabitants [5–7]. Therefore, to plan possible measures for protecting these natural ecosystems, innovative technologies and methods for monitoring water quality are needed [8–10]. Unlike classical in situ ground measurement methods that involve expensive field visits to a few sites in a lake, Earth Observation (EO) data can provide frequent surveys over a large area in a cost-effective way [11–13].

The latest generation of multispectral sensors on board of Sentinel-2 satellites is now used to assess the intra-annual spatial and temporal dynamics of phytoplankton abundance in shallow eutrophic lakes [14,15]. In order to estimate *chl-a* pigment, the development of satellite reflectance algorithms associated with phytoplankton biomass should be carried out [8]. *Chl-a* found in phytoplankton can be sensed by a variety of current and near-future satellite imaging technologies. The newest generation of medium-resolution multispectral sensors on board satellites such as Landsat-8 and Sentinel-2 are now offering promising analyses for monitoring water quality [9,16] because of their fine spatial resolution, revisit time, and improved spectral band configuration in the visible–near-infrared wavelength range.

Chl-a has been widely estimated through remote sensing techniques [17–19]. However, few algorithms have been proposed for estimating chlorophyll-a as a proxy for productivity in eutrophic inland water using Sentinel-2. Since Sentinel-2 MSI has a band at 705 nm (B5), it can capture a *chl-a* peak.

In an aim to better understand the dynamics of cyanobacterial blooms, an algorithm based on Sentinel 2 was developed and validated. The algorithm was then used to map the spatial and temporal dynamics of these blooms throughout the reservoir.



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2. Materials and Methods

2.1. Study Site

Karaoun Reservoir is the largest freshwater body in Lebanon. The reservoir is used for power production and irrigation. It has a surface area of 12 km² at full capacity and a maximum and mean depth of 60 and 19 m, respectively [20]. The reservoir is classified as a hypereutrophic and monomictic water body with occurrence of cyanobacterial blooms during the spring and summer seasons, representing an interesting study case.

2.2. Field measurements

In situ measurements of the *chl-a* concentration were collected for band testing and algorithm development. Data were collected on 15 July 2016, 18 September 2017, 18 October 2017, and 29 August 2018, from a total of 23 sampling sites ($n = 23$). Similarly, an independent dataset was collected on 30 June 2017, 28 October 2017, 9 August 2018, 3 October 2018, and 23 October 2018 for validation purposes and consisted of a total of twelve sampling locations ($n = 12$). All campaigns were performed during Sentinel-2 overpasses.

Chlorophyll-a quantification was carried out according to the Lorenzen method [21]. A triplicate of each sample was filtered using Whatman GF/C filters. Chlorophyll-a was then extracted using 90% acetone by ultrasonication. The extracts were centrifuged at 3500 rpm for 12 min and then quantified using a spectrophotometer.

Spectroradiometric measurements were taken at several sites throughout the reservoir, synchronously with satellite overpasses, on 18 September 2017 and 18 October 2017 using a field spectroradiometer (ASD Field Spec 4) within a spectral range of 350–2500 nm and according to the SeaWiFS protocol [22]. To remove the glint effect, the method of [23] was applied.

2.3. Satellite data acquisition

A total of 38 cloud-free Sentinel-2 Satellite images were downloaded freely from the USGS. They are all level-1T-processed. Dates covered are between 20 August 2015 and 28 October 2018. The Sentinel-2 imagery consists of nine scenes collected in parallel with in situ measurements taken in 2016, 2017, and 2018.

2.4. Processing Images

Radiometric and atmospheric corrections were applied to the downloaded level 1 satellite images. The pre-processing steps of Sentinel-2 images consisted of radiometric calibration on SNAP, resampling bands on ENVI, atmospheric correction on 6S, and applying an algorithm on ArcGIS. The Sentinel-2 images were corrected using the 6S code (Second Simulation of the Satellite Signal in the Solar Spectrum), a radiative transfer code for modeling atmospheric scattering effects [24–26]. The Aerosol Optical Depth (AOD) values that were needed as input for 6S were extracted from NASA's AERONET (Aerosol Robotics NETwork) program.

2.5. Algorithm development

A semi-empirical band ratio approach was chosen after testing multiple ones. Reflectance data were acquired from the first eight bands of Sentinel-2. The model was applied in the form of simple linear regression, $Y = aX + b$, where Y is the measured *chl-a* concentration, X is the applied band or band combination, a is the regression coefficient for X , and b is the constant term. The coefficient of determination R^2 and the Pearson correlation coefficient were applied, searching for the best band combination.

3. Results

3.1. In Situ Results

Figure 1 shows the distribution of *chl-a* during nine field campaigns in 2016, 2017, and 2018. Four dates were used for calibration and five dates for validation. Both figures show wide ranges and variability across the sampled areas. The *chl-a* concentrations ranged from

8.3 to 169 $\mu\text{g/L}$, with a mean value of 63.83 $\mu\text{g/L}$. The highest spatial variation in [*chl-a*] occurred on 18 October 2017 and 28 October 2018, with a standard deviation of 30.67 and 64.35, respectively.

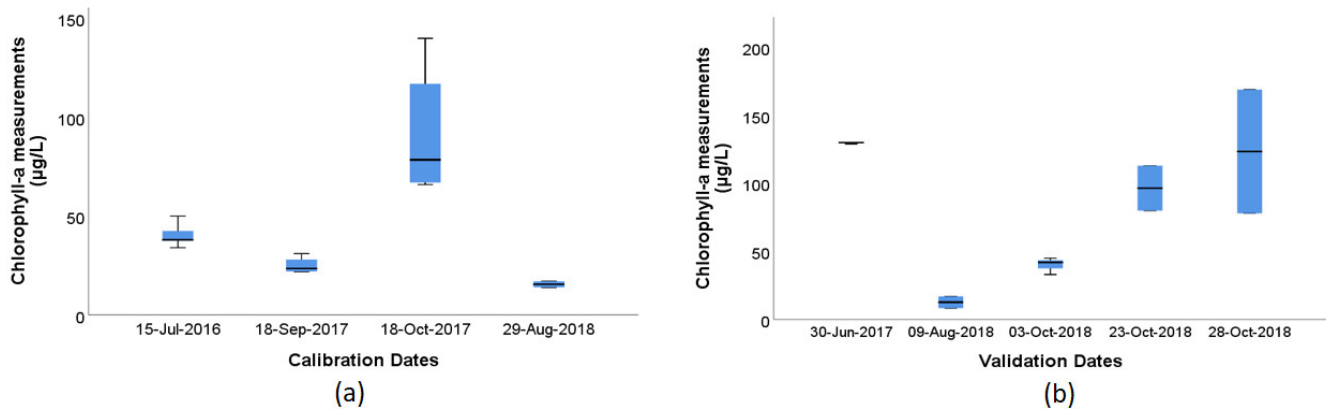


Figure 1. A box plot showing ground measurements of chlorophyll-a concentrations used for (a) calibration and (b) validation.

3.2. *Chl-a* Concentration Algorithm: Calibration and Validation

On a single-band level, Band 5 was correlated the most with the in situ PC measurements, with $R^2 = 0.69$ and $R = 0.831$. For band combinations, the best fit between the bands' reflectance and actual PC measurements was found for the band ratio B5/B4, with $R^2 = 0.862$. Based on these findings, the empirical band ratio model was developed using a Red band 4 of spectral resolution (650–680 nm) with a Vegetation Red Edge band 5 (698–713 nm) to estimate *chl-a* at Karaoun Reservoir. The algorithm is shown in (Equation (1)):

$$\text{Chl-a } (\mu\text{g/L}) = 79.9 (\text{B5/B4}) - 57.2 \quad (1)$$

An independent dataset ($n = 12$) acquired on 30 June 2017, 9 August 2018, and on 3, 23, and 28 October 2018, was used to evaluate and validate the performance of the developed band ratio algorithm using the established regression coefficients. During the mentioned dates, cyanobacterial blooms dominated the Karaoun Reservoir, with a high *chl-a* concentration ranging from 8.3 to 169 $\mu\text{g/L}$.

Figure 2 shows the scatter correlation plot between the measured and predicted *chl-a* contents from the developed band ratio algorithm with a high coefficient of determination, $R^2 = 0.8$.

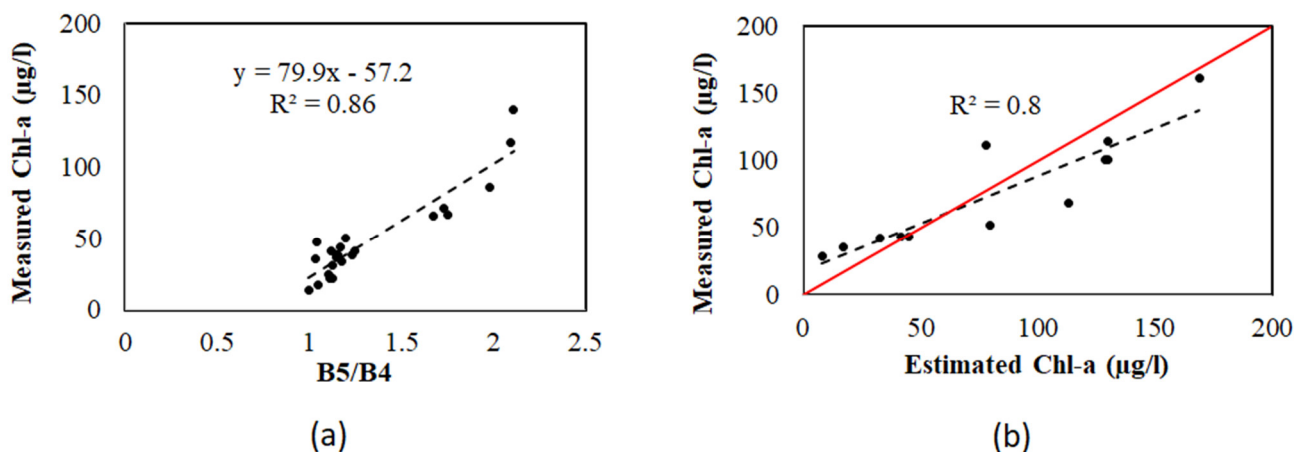


Figure 2. *Chl-a* algorithm (a) calibration and (b) validation.

Figure 3 shows the spatio-temporal variations in *chl-a* concentration for the cloud-free days between 2015 and 2017, produced using the validated algorithm. The *chl-a* values mostly ranged between 5 and 190 $\mu\text{g/L}$. Except for May and August 2017, a heterogeneous spatial distribution was noticed throughout the reservoir.

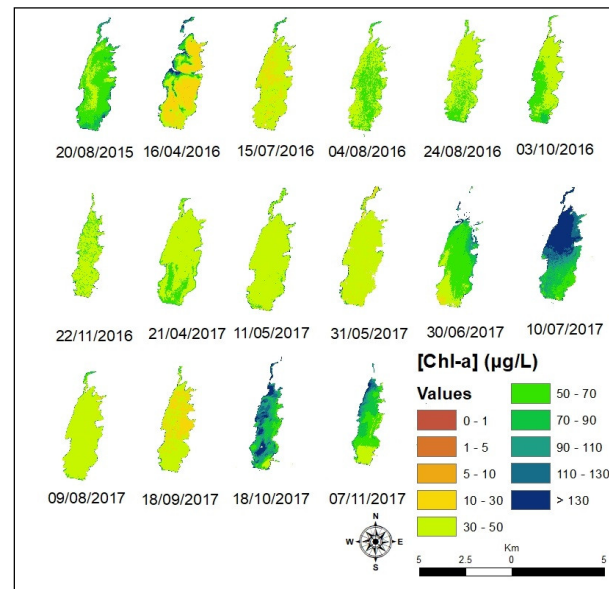


Figure 3. Maps of chlorophyll-a concentration between year 2015 and year 2017 on Karaoun Reservoir.

4. Discussion

The assessment of *chl-a* by remote sensing uses its characteristic absorption features between 440 nm and 560 nm and at 670 nm [27]. The *chl-a* reflectance peak region (700–720 nm) may move toward a longer wavelength when phytoplankton is abundant. The results of [28] showed that the amplitude of the 705 nm peak against the 665–740 nm (B4–B6 of Sentinel-2) baseline was in very good correlation with the *chl-a* concentration in the studied lakes ($R^2 = 0.83$). Since Sentinel-2 MSI has a band at 705 nm (B5), it can capture a perfect *chl-a* peak. The algorithm developed in this study is comparable to others. Pinardi et al., 2018, also developed an algorithm on an Italian lake using the band ratio of Bands 4 and 5 Sentinel-2 images [14].

This study is the first attempt to evaluate the performance of the Sentinel-2 MSI sensor on *chl-a* retrieval algorithms coupled with in situ data at Karaoun Reservoir, located in an understudied region. The results achieved in this study have presented the use of simple linear regression analysis to develop an algorithm for *chl-a* estimation. After testing the bands of Sentinel-2, we chose the most suitable ratio from the highly correlated band ratios with the actual *chl-a* concentration.

The results are very encouraging for inland water monitoring and research. This algorithm will assist in monitoring phytoplankton blooms and supporting water management decisions for the optimal utilization of Karaoun Reservoir. The applicability of this algorithm was tested under high *chl-a* values and can be used on other eutrophic inland waters.

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