environmental sciences proceedings

MDPI

Proceeding paper

Mapping aquatic cyanobacterial blooms using Sentinel-2 satellite imagery †

Ali Fadel [1,*], Doha Maatouk [2], Kamal Slim [2], and Ghaleb Faour [2]

[1] Institut de Recherche sur la Biologie de l'Insecte, UMR 7261, CNRS - Université de Tours, 37200 Tours, France ; ali.fadel@univ-tours.fr
[2] Remote Sensing Center, Lebanese CNRS, Beirut, Lebanon; gfaour@cnrs.edu.lb; k.slim@laec-cnrs.gov.lb; doha.maa@gmail.com
* Correspondence: ali.fadel@univ-tours.fr

† Presented at the 5th International Electronic Conference on Remote Sensing, Online, 7-21 November 2023.

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 better manage them. In our work, we develop 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, chloropyll-a

1. Introduction

Lakes and reservoirs are valuable natural resources that offer essential ecological, environmental, and hydrological services. Cyanobacterial blooms are a serious problem in freshwater bodies, often suffering from eutrophication and mismanagement of watersheds [1]. They can produce lethal cyanotoxins that threaten human health and aquatic inhabitants [2,3]. Therefore, to plan possible measures for protecting these natural ecosystems, innovative technologies, and methods for monitoring water quality are needed. 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 [4,5].

The latest generation of multi-spectral 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 [4]. In order to estimate chl-a pigment, the development of satellite reflectance algorithms associated with phytoplankton biomass should be done [6]. Chl-a found in phytoplankton, can be sensed by a variety of current and near-future satellite imaging. The newest generation of medium-resolution multispectral sensors on board such that Landsat-8 and Sentinel-2 satellites are now offering promising analysis for monitoring water quality [7,8] 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 [9]. However, few algorithms have been proposed for estimating chlorophyll-a as a proxy for productivity in eutrophic inland water using Senitnel-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.

Citation: To be added by editorial staff during production.

Academic Editor: Firstname Lastname

Published: date

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 km^2 at full capacity, a maximum and mean depth of 60 and 19 m, respectively [10]. The reservoir is classified as hypereutrophic and monomictic water body with occurrence of cyanobacterial blooms during Spring and Summer seasons [11,12], representing an interesting study case.

2.2. Field measurements

In situ measurements of chl-a concentration were collected for band testing and algorithm development. Data were collected on Jul. 15th, 2016, Sep. 18th, 2017, Oct. 18th, 2017, and Aug.29th 2018, of a total of 23 sampling sites (n=23). Similarly, an independent dataset was collected on Jun.30th 2017, Oct. 28th, 2017, Aug. 9th, 2018, Oct.3rd 2018, and Oct. 23rd 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 (Lorenzen, 1967). 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, in synchronous with satellite overpass, on 18 Sep. 2017 and 18 Oct. 2017 using a field spectroradiometer (ASD Field Spec 4) within a spectral range of 350-2500 nm, and according to the SeaWiFS protocol [13]. To remove the glint effect, the method of [14] 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 Aug. 20th, 2015 and Oct. 28th, 2018. The Sentinel-2 imagery consists of nine scenes collected in coincidence 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. 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. 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 [15]. The Aerosol Optical Depth (AOD) values 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 R2 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. Chl-a concentrations ranged from 8.3 to 169 µg/L with a mean value of 63.83 µg/L. Highest spatial variation of [chl-a] occurred on 18 Oct. 2017 and 28 Oct. 2018 with a standard deviation of 30.67 and 64.35, respectively.

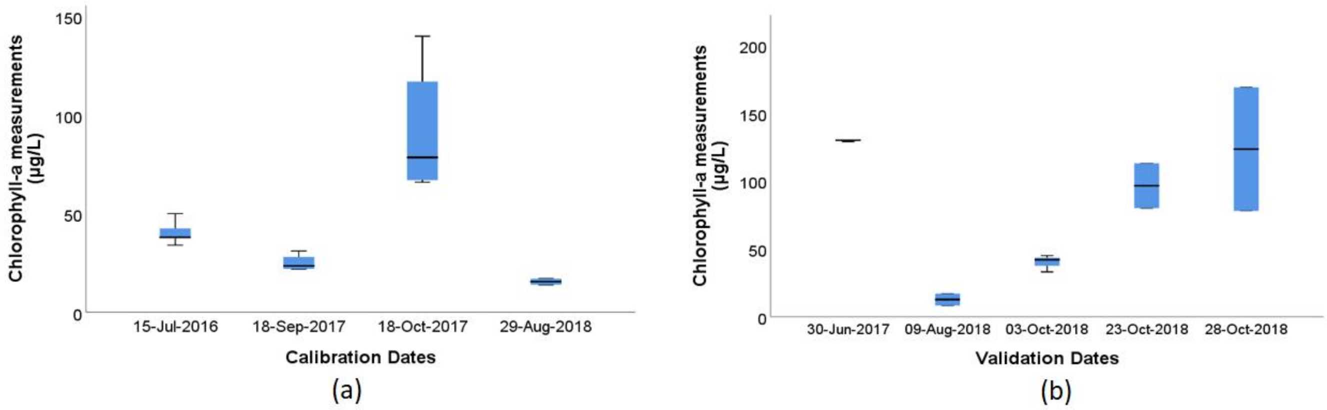

Figure 1. A box plot showing ground measurements chlorophyll-a concentrations used for (a) calibration and (b) validation.

3.2. Chl-a concentration algorithm: calibration and validation

On a single-band level, Band 5 was correlated the most with in situ PC measurements, with R2= 0.69 and R=0.831. For band combinations, the best fit between bands reflectance and actual PC measurements was found for the band ratio B5/B4 with R2=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 Vegetation Red Edge band 5 (698-713 nm) to estimate chl-a at Karaoun Reservoir. The algorithm is shown in (Equation 1)

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

An independent dataset (n=12) acquired on June 30th 2017, August 9th, 2018, and on 3rd, 23rd, 28th of 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 µg/L.

Figure 2 shows the scatter correlation plot between measured and predicted chl-a content from the developed band ratio algorithm with a high coefficient of determination, R2 = 0.8.

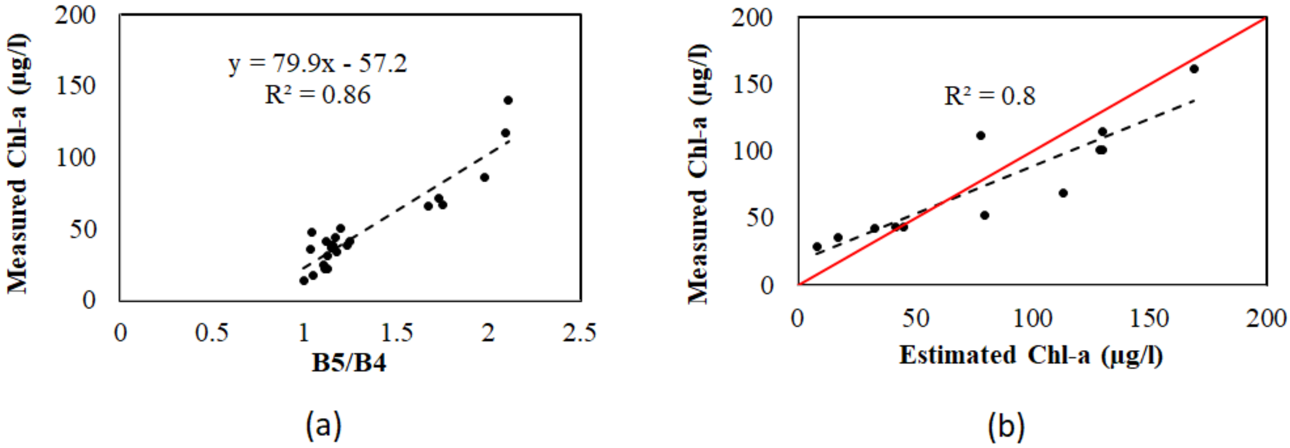

Figure 2. Chl-a algorithm a) calibration and b) validation**.**

Figure 3 shows the spatio-temporal variations of *chl-a* concentration for the cloud free days between 2015 and 2017 produced using the validated algorithm. C*hl-a* values mostly ranged between 5 and 190 µg/L. Expect for may and august 2017, a heterogenous spatial distribution was noticed throughout the reservoir.

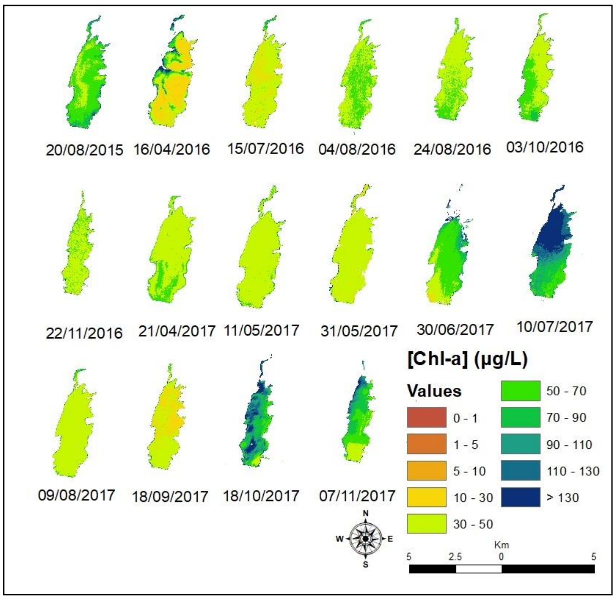

Figure 3. Maps of chlorophyll-a concentration between year 2015 to year 2017 on Karaoun Reservoir.

Discussion

Assessment of chl-a by remote sensing uses its characteristic absorption features between 440 nm and 560 nm and at 670 nm [16]. *Chl-a* reflectance peak region (700–720 nm) may move toward a longer wavelength when phytoplankton is abundant. Results of [17] 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 *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 Senintel-2 images [4].

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 have chosen 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 in inland waters.

Author Contributions: Conceptualization, A.F.; methodology, A.F. ; software, A.F.; validation, A.F., G.F., K.S. and D.M.; formal analysis, A.F. and G.F.; investigation, A.F. and G.F.; resources, A.F., K.S. and G.F.; data curation, A.F. and R.H.G.; writing—original draft preparation, A.F.; writing—review and editing, A.F., K.S. and G.F.; visualization, A.F. and G.F.; supervision, A.F., K.S. and G.F.; project administration, A.F.; funding acquisition, A.F. and G.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received a financial support from the Lebanese CNRS.

Data Availability Statement: Data can be provided upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Darwish, T.; Atallah, T.; Fadel, A. Challenges of Soil Carbon Sequestration in NENA Region. *SOIL* **2018**, *4*, 225–235, doi:10.5194/soil-2017-39.
2. Fadel, A.; Atoui, A.; Lemaire, B.; Vinçon-Leite, B.; Slim, K. Dynamics of the Toxin Cylindrospermopsin and the Cyanobacterium Chrysosporum (Aphanizomenon) Ovalisporum in a Mediterranean Eutrophic Reservoir. *Toxins* **2014**, *6*, 3041–3057.
3. Fadel, A.; Guerrieri, F.; Pincebourde, S. The Functional Relationship between Aquatic Insects and Cyanobacteria: A Systematic Literature Review Reveals Major Knowledge Gaps. *Total Environ. Res. Themes* **2023**, *8*, 100078, doi:10.1016/j.totert.2023.100078.
4. Pinardi, M.; Bresciani, M.; Villa, P.; Cazzaniga, I.; Laini, A.; Tóth, V.; Fadel, A.; Austoni, M.; Lami, A.; Giardino, C. Spatial and Temporal Dynamics of Primary Producers in Shallow Lakes as Seen from Space: Intra-Annual Observations from Sentinel-2A. *Limnologica* **2018**, *72*, 32–43, doi:10.1016/j.limno.2018.08.002.
5. Fadel, A.; Mhawej, M.; Faour, G.; Slim, K. On the Application of METRIC-GEE to Estimate Spatial and Temporal Evaporation Rates in a Mediterranean Lake. *Remote Sens. Appl. Soc. Environ.* **2020**, *20*, 100431–100431, doi:10.1016/j.rsase.2020.100431.
6. Matthews, M.W.; Odermatt, D. Improved Algorithm for Routine Monitoring of Cyanobacteria and Eutrophication in Inland and Near-Coastal Waters. *Remote Sens. Environ.* **2015**, *156*, 374–382, doi:https://doi.org/10.1016/j.rse.2014.10.010.
7. Kutser, T. Quantitative Detection of Chlorophyll in Cyanobacterial Blooms by Satellite Remote Sensing. *Limnol. Oceanogr.* **2004**, *49*, 2179–2189, doi:10.4319/lo.2004.49.6.2179.
8. Pahlevan, N.; Lee, Z.; Wei, J.; Schaaf, C.B.; Schott, J.R.; Berk, A. On-Orbit Radiometric Characterization of OLI (Landsat-8) for Applications in Aquatic Remote Sensing. *Remote Sens. Environ.* **2014**, *154*, 272–284, doi:https://doi.org/10.1016/j.rse.2014.08.001.
9. Bresciani, M.; Stroppiana, D.; Odermatt, D.; Morabito, G.; Giardino, C. Assessing Remotely Sensed Chlorophyll-a for the Implementation of the Water Framework Directive in European Perialpine Lakes. *Sci. Total Environ.* **2011**, *409*, 3083–3091, doi:10.1016/j.scitotenv.2011.05.001.
10. Slim, K.; Fadel, A.; Atoui, A.; Lemaire, B.J.; Vinçon-Leite, B.; Tassin, B. Global Warming as a Driving Factor for Cyanobacterial Blooms in Lake Karaoun, Lebanon. *Desalination Water Treat.* **2014**, *52*, 2094–2101, doi:10.1080/19443994.2013.822328.

11. Fadel, A.; Sharaf, N.; Siblini, M.; Slim, K.; Kobaissi, A. A Simple Modelling Approach to Simulate the Effect of Different Climate Scenarios on Toxic Cyanobacterial Bloom in a Eutrophic Reservoir. *Ecohydrol. Hydrobiol.* **2019**, *19*, 359–369, doi:10.1016/j.ecohyd.2019.02.005.
12. Fadel, A.; Kanj, M.; Slim, K. Water Quality Index Variations in a Mediterranean Reservoir: A Multivariate Statistical Analysis Relating It to Different Variables over 8 Years. *Environ. Earth Sci.* **2021**, *80*, 65–65, doi:10.1007/s12665-020-09364-x.
13. Fargion, Giuletta S and Mueller, J.L. *Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Revision 2*; National Aeronautics and Space Administration, Goddard Space Flight Center, 2000;
14. Kutser, T.; Vahtmäe, E.; Paavel, B.; Kauer, T. Removing Glint Effects from Field Radiometry Data Measured in Optically Complex Coastal and Inland Waters. *Remote Sens. Environ.* **2013**, *133*, 85–89, doi:https://doi.org/10.1016/j.rse.2013.02.011.
15. Sharaf, N.; Bresciani, M.; Giardino, C.; Faour, G.; Slim, K.; Fadel, A. Using Landsat and in Situ Data to Map Turbidity as a Proxy of Cyanobacteria in a Hypereutrophic Mediterranean Reservoir. *Ecol. Inform.* **2019**, *50*, 197–206, doi:10.1016/j.ecoinf.2019.02.001.
16. Dörnhöfer, K.; Oppelt, N. Remote Sensing for Lake Research and Monitoring – Recent Advances. *Ecol. Indic.* **2016**, *64*, 105–122, doi:https://doi.org/10.1016/j.ecolind.2015.12.009.
17. Toming, K.; Kutser, T.; Laas, A.; Sepp, M.; Paavel, B.; Nõges, T. First Experiences in Mapping Lake Water Quality Parameters with Sentinel-2 MSI Imagery. *Remote Sens.* **2016**, *8*, doi:10.3390/rs8080640.