Hungarian University of Agriculture and Life Sciences based on satellite and drone images

Comparative analysis and development of freshwater chlorophyll-a determination using remote sensing methods

Thesis of doctoral dissertation

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1. Background and objectives

The ecological status, economic usability and tourist attractiveness of lakes are significantly determined by the amount of algae presence, for the analysis of which the amount of chlorophyll-a, the amount of algae present, for which the amount of chlorophyll-a, which is closely correlated, is determined. The lakes also play a key social and economic role as a drinking water base, as a tourist destination and, with fisheries, as contributing to economic growth. Algae form the basis of the aquatic food chain, fundamentally determining the ecological status of the lake. However, their overgrowth, the so-called algal bloom, poses serious problems. Therefore, regular monitoring of algae, their quantification and species determination are of paramount importance.

There are two basic methods for measuring chlorophyll-a. Laboratory testing of local samples and remote sensing methods. Compared to traditional field sampling and laboratory testing, remote sensing studies have several advantages.

The objectives of my research are the followings:

I. New measurement procedure

Development of a complex remote sensing system and methodology to verify that chlorophyll-a concentration, calibrated with laboratory results, can be successfully measured by drone multispectral remote sensing too. The method would provide higher resolution recordings than measurements made by airplane or satellite, allowing for day-to-day monitoring activity.

II. New data processing procedure

Development of a new algorithm for the determination of chlorophyll-a optimized for the present field of research, a low-computational and easier-to-automate correction method for satellite and drone multispectral recordings. Compared to the sampling options, the procedure is tested at several sites in Lake Balaton (all four basins, north and south)..

III. New data extraction procedure

Extraction of reflectance values based on the coordinates of pre-processed remote sensing images as part of the research work, in order to automate the work, participating in the research work of the Water Management Research Group of the Hungarian Academy of Sciences and the Budapest University of Technology and Economics (MTA-BME). Application of the completed script to Sentinel-2 satellite imagery to determine chlorophyll-a.

IV. Verification of the effectiveness of remote sensing

By building (between 2015 and 2020) and processing a satellite database, a comparison of the spatial and temporal study of chlorophyll-a on results previously confirmed by laboratory studies and field measurements. Spectral study of typical algal species in the experimental area, creation of a prototype spectral library for further scientific study. The aim of this activity is to establish a more specific definition of the quantity and quality of algae.

V. Establishment of a satellite and spectral reference database

Creation of a six-year thematic chlorophyll reference database and a spectral library of characteristic algal species in Lake Balaton. A unique reference database can provide a good basis for monitoring short-, medium-, and long-term hydrological processes and tracking changes. Its continuous expansion can serve as a basis for further scientific research.

2. Materials and methods

2.1. Drone measurement methodology

The drone used for collecting dataset was a DJI Mavic 2 Enterprise Thermal Dual device as well as a LaQuinta multispectral camera. I solved the mounting of the camera on the platform with a camera adapter of my own design, made with 3D printing. 3D design in SketchUp Pro 2019 and Creality Slicer 1.2.3. while printing itself was performed by an Ender 3 Pro 3D printer. The flight altitude of the drone was four meters each time, about 10 meters away from the shore. Metadatas can be read from the camera's own software, NDVIImageViewer, which also stored light intensity, irradiance, GPS coordinate, gain, shutter and other values. Reflectance values were also calculated based on reference data. The reference data were provided by a recording of a white panel with known spectral properties.

The next step was to develop the algorithms needed to determine chlorophyll-a values. In my research based on literature data, I found that the blue / green and near infrared / red ratio correlated well with the amount of chlorophyll-a (Zeng et al. 2016; Gordon, Morel 2012; Ha et al. 2017; Han, Rundquist 1997). When plotting the correlation between these quotients and the values measured in the laboratory, it became apparent that the same formula could not be applied to all measurement points. The estuary of the river Zala, Kis-Balaton and, depending on the water depth, different areas of Lake Balaton had to be chosen separately. A separate formula has to be applied on the south shore of an average of one and a half meters and on the north shore with an average depth of 1.5 to 2.5 meters, as well as in extremely shallow areas with a depth of 50 cm. In the studies (mentioned above) I examined, I found that some specific multiplier was needed for the ratios. In the light of the ratios and the laboratory knowledge, I developed a correlation and multiplier specifically and locally for each measurement, which would show a sufficiently accurate agreement with the laboratory results. Combining each ratio with all possible multiplier values (between minimum and maximum values), I obtained all the mathematically possible variants. After that, I looked at the deviation from the laboratory value for each variation, subtracting the value measured in the laboratory from the value obtained on the basis of the drone measurement. I did this with the results of each ratio with each multiplier and also included it in a table. The next step is to add the differences between the calculated values obtained with a multiplier and the corresponding laboratory rate. I performed this operation with all the multipliers obtained. This is how the appropriate local multiplier value was formed for each area. Simultaneously with the drone measurements, I took a water sample from the measurement site. These samples were stored refrigerated at 4 ° C for 1 to 5 days until laboratory analysis. The chlorophyll-a content was determined by the

Felföldy method. In the process, the sample is compacted through a suitable filter, the pigments are dissolved in boiling methyl alcohol and the amount is measured with a spectrophotometer. (Felföldy, 1963) These laboratory measurements formed the database required for the validation of drone measurements. Statistical analysis of the data was performed using IBM SPSS v25. (Armonk 2017) To investigate the relationship between laboratory results and results based on multispectral camera recordings, I used the Pearson correlation method. A prerequisite for this analysis is the homogeneous distribution of the samples, which I examined with the Shapiro-Wilk normality test. A budget analysis was also performed to compare drone and laboratory measurements. During the analysis, the depreciation of the assets, the cost of electricity consumption, the assets and the travel costs were taken into account. Depreciation was calculated using the linear method also used by accountants.

2.2. Validation of chlorophyll-a determination based on satellite image and zonal statistics

One goal was to validate the chlorophyll-a maps of Sentinel-2 satellite images created with Acolite for a freshwater lake. The Acolite program is a program specifically designed to process satellite imagery of marine water surface, which also offers four different algorithms for determining chlorophyll-a. I obtained the necessary recordings from two sources: USGS Earthexplorer (https://earthexplorer.usgs.gov/) and Copernicus Open Access Hub. (https://scihub.copernicus.eu/dhus/#/home) This was followed by processing with Acolite. (https://odnature.naturalsciences.be/remsem/software-and-data/acolite) The Sentiel-2 satellite captures Lake Balaton in three parts, so the merging of the three images can be done with the mosaic raster layers tool found in the QGIS processing toolbar. For clear visibility and easy distinguishability of the data, four categories have been created, each indicating its own different chlorophyll-a range. The four categories and their ranges are presented according to the ranges defined by the OECD (Organization for Economic Co-operation and Development). The validation of the values of the satellite images was based on the local samples used for the drone images, so the conditions and methods presented in 2.1.chapter are omitted here. In addition to the values determined by the four algorithms, I developed two formulas to determine chlorophyll-a. The first step was to create a script that looked up the reflectance values measured by the satellite image for each channel based on the input coordinate, exactly to that point. The script was runned in RStudio Desktop 4.0.0. software, (https://rstudio.com/products/rstudio) the script was written in collaboration with the MTA-BME Water Management Research Group. I used regional statistics to examine seasonal trends and regional differences that have emerged since 2015. To this end, I created a so-called shapefile with the four basins of Lake Balaton, which were divided into northern and southern quarters. Thus, I divided Lake Balaton into a total of eight parts. Going from west to east, the four basins are: the Keszthely Basin, the Szigliget Basin, the Szemesi Basin and the Siófok Basin. I divided all four areas into northern and southern parts. In the present case, the spatial distribution of the average, minimum and maximum chlorophyll-a amounts was determined.

2.3. Spectral library

The Waves program allows you to manage the VNIR prodeced, QMini device (400-1000 nm) and display results. (ttps://www.rgb-photonics.com/products/spectrometers/product/qmini/) This was followed by the inclusion of white reference and black reference. After recording the reference values, the device must be set to use these values during the measurement, after which the measurement can take place. During the process, the sensor was positioned vertically at a distance of 30 centimeters from the sample. The halogen lamp that provided the illumination hit the sample to be tested at a 45-degree angle. The exposure time was set to 0.5 s, the test sample was 10 mm. The algae studied were the algae Selenastrum, Chlorella, Scenedesmus, Microcrystis, Oscillatoria and phycoerythrins. When the spectral library was recorded, the aim was not only to create a database. The aim of the research was to investigate whether the spectral curve of each algal species changes at different concentrations and if the spectrometer is directed not to the center of the sample holder but to the edge. Each alga was also tested in concentrated, 2X, 4X, 8X, and 16X diluted forms. In addition, I recorded not only the spectrum from pure algal culture, but also mixtures of algae.

3. Results

3.1. Results of drone measurement methodology

Normality tests had to be performed as a prerequisite for the Pearson correlation. Based on the results of the Shapiro-Wilk normality test, an logarithmical transformation had to be applied, after which the conditions of normality were met and the Pearson correlation test became feasible. The results of the correlation study are shown in ***Table 1.***

Table 1: Results of Pearson's correlation study between laboratory and drone measurement data

Correlation							
		rbg	**llbg**	**ibg**	**rnir**	**llnir**	**inir**
lab	**Pearson-correlation**	0.94***	0.96***	0.93***	0.88***	0.90***	0.91***
lnlab: ln laboratory measurements; lnrbg: ln reflectance B/G; lnllbg: ln light level B/G; lnibg: ln irradiance B/G; lnrnir: ln reflectance NIR/R; lnllnir: ln light level NIR/R; lninir: ln irradiance NIR/R							
*** significant at p<0.001 N:32							

The results of all six algorithms showed a significant correlation with the laboratory measurement data. The highest correlation coefficient was obtained from the results based on the blue / green ratio. (r = 0.96, p <0.01) The simplified cost analysis is shown in ***Table 2***, from which it can be read that the cost of drone measurements is 27.6% less than the value of laboratory measurements, so HUF 1380 can be saved per measurement.

Table 2: Simplified cost analysis of laboratory and drone measurements

	laboratory measurement	**drone measurement cost**
travel expenses	1.000 HUF	1.000 HUF
amortisation	1.500 HUF	1.600 HUF
electricity	500 HUF	20 HUF
chemical	1.000 HUF	0 HUF
other equipment	1.000 HUF	700 HUF
total cost/measurement	***5.000*** HUF	***3.320*** HUF

3.2. Validation of chlorophyll-a determination based on satellite image and results of zonal statistics

To test for normality, the Shapiro-Wilk normality test was used, the conditions for normality were met, and the Pearson correlation test became feasible. With the data processing with Acolite, the correlation coefficients showed satisfactory results. ***Table 3*** shows the correlation coefficients.

Table 3: The correlation coefficient of laboratory and remotely sensed datas

	Pearson correlation coefficients
chl_oc2	0.86***
chl_gons	0.83***
chl_mishra	0.75***
chl_moses3b	0.78***
chlextbg	0.93***
chlextnirr	0.85***
*** p<0.001	

The aim of the zonal statistical studies was to investigate the spatial and temporal distribution of algae. According to previous (not remote sensing) studies, a significant west-east trophic gradient can be observed in the case of Lake Balaton. (Herodek et al. 1988; Istvánovics et al. 2007; Palmer et al. 2015b) This result was also proved by the present research. In addition, when comparing the southern and northern areas, higher concentrations of chlorophyll-a were observed in the southern areas. The results are shown in **Figure 1.** Mean and standard deviation of chl-a amount in Lake Balaton depending on basins (Keszthely, Szigliget, Szemes and Siófok) and quarters (north and south). Different letters are for significantly different basins (Turkey's, $p<0.05$) while * and + denote the difference between the north and south part of the lake at $p<0.05$ and $p<0.10$, respectively according to chl_oc2 algorithm.

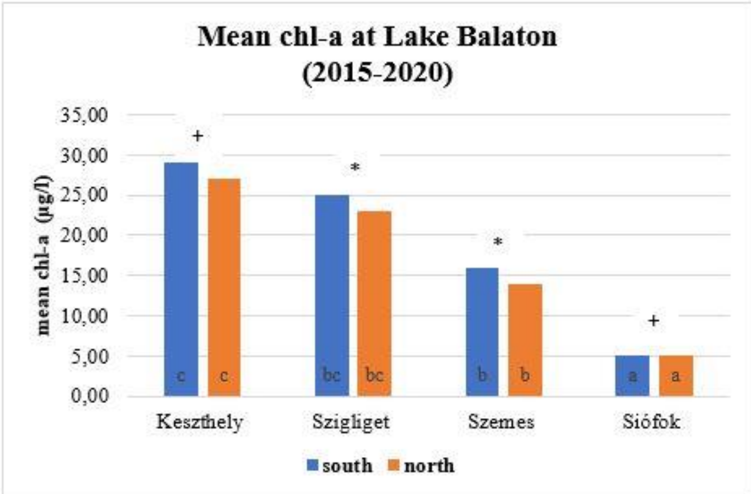

Figure 1: Amount of average chlorophyll-a per bay, devided into northern and southern regions

The result shows that the most significant significant interactions were in the Szigliget basin (F (1; 70) = 6.3; p = 0.015) and the Szemes basin (F (1; 70) = 4.0; p <0.05). In the case of the Keszthely basin (F (1; 70) = 3.3; p <0.07) and the Siófok basin (F (1; 70) = 3.1; p <0.08), the interaction was moderately significant. The average chlorophyll-a value for the period 2015-2020 is 17 µg / l in ing, 16 µg / l in summer, 20 µg / l in autumn and 10 µg / l in winter. The highest amount of chl-a is observed in autumn. This is due to the fact that one of the characteristic algal species of Lake Balaton, Cylindrospermopsis raciborskii, reaches its maximum amount in early autumn. In all four seasons, there was a difference between the north and the south. Chlorophyll-a content was always higher in the southern areas than in the northern areas, but not to the same extent. The northern and southern regions have the largest different in spring, when the southern region is 19% more than the northern chlorophyll-a value. The smallest difference was observed in winter and autumn, when the southern region was 1% larger than that of northern chlorophyll -a.

3.3. Results of spectral library

The results showed the same trend for all algae tested. By increasing the concentration, it was observed that the rate of reflection increased in the section between 650 and 750 nm. However, this increase was becoming less and less significant with increasing concentration. The spectral curve of Scenedesmus and Chlorella has the same course, while the curve of Selenastrum between 600 and 700 nanometers shows 0.05 nW / nm instead of 0.04 nW / nm, unlike the other two algal species. The curve obtained by examining the three algae together gives the same curve as Scenedesmus and Chlorella.

3.4. New scientific achievements and theses

I. New measurement procedure

I developed a complex remote sensing procedure and methodology, which proved that the algae concentration can be successfully measured with a drone multispectral remote sensing method calibrated / corrected with laboratory results. The procedure provides higher resolution recording than airborne remote sensing and is more cost effective and better designed. It provides higher resolution recordings than satellite technology and even allows for daily monitoring.

The method requires less investment than a hyperspectral drone method and also requires less computational capacity for data processing.

II. New data processing procedure

I have developed a new algorithm for the determination of chlorophyll-a based on the blue / green and infrared / red reflectance ratios optimized for freshwater. With a low computational and algorithmic correction procedure applicable to satellite and drone multispectral recordings, in which I significantly improved the correlation between chlorophyll (algae concentration) and remotely sensed data using the results of laboratory tests of water samples. I successfully applied the procedure in several locations on Lake Balaton. The method can be extended to other living waters.

III. New data extraction procedure

Joining the research work of the Water Management Research Group of the Hungarian Academy of Sciences-BME, I defined the logical steps of the script for extracting reflectance values based on the coordinates of remote sensing recordings as an idea manager, I assisted the programming as a consultant. I successfully applied the script to the Sentinel-2 B twin satellites. The unique method of data extraction is the scientific result of my independent research.

IV. Verification of the trophic gradient phenomenon of chlorophyll by a new method

By building and processing a unique satellite database, I verified the east-west trophic gradient and the different amounts of chlorophyll-a in the northern and southern areas and the seasonal pattern in Lake Balaton by remote sensing. The spectral study of the characteristic algal species of the experimental area, the creation of a prototype spectral library for further scientific research is the result of the present research. After further expansion and research, the spectral library may provide an opportunity to determine more specific algal abundance and quality

V. Establishment of a thematic chlorophyll-a reference database

I created a reference database of thematic chlorophyll-a maps covering six years and a spectral library of the characteristic algal species of Lake Balaton. The creation of a unique reference database serves as a basis for monitoring short-term, medium-term and long-term hydrological processes (eg regulations or the effects of climate change) and for monitoring change. Its continuous expansion can serve as a basis for further scientific research.

4. Conclusions and recommendations

Based on the correlation studies, the drone measurement method allows the determination of high-precision chlorophyll-a concentration. 3D printing has proven its applicability in mounting the camera on a drone. Correlation studies have demonstrated the applicability of both drone and satellite images in the determination of chlorophyll-a in lakes. The two methods have different advantages and disadvantages. In the performance of regular, precise algae monitoring, the two methods do not replace but complement each other. A more specific determination of algae by remote sensing methods would be a major step that would require further research.

5. Publications related to the topic of the tesis

International scientific publications:

Tóth, V. Zs., Ladányi, M., Jung, A. (2021). Adaptation and Validation of a Sentinel-Based Chlorophyll-a Retrieval Software for the Central European Freshwater Lake, Balaton. PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science, 89(4), 335-344. (Q1)

Tóth, V. Zs., Grósz, J., Ladányi, M., Jung, A. (2021). A new lake algae detection method supported by a drone-based multispectral camera. *Lakes & Reservoirs: Research & Management*, 26(3), e12377. (Q3)

Conferences:

Tóth, V. Zs. (2018). Közép-Európa legnagyobb tavának távérzékeléses vizsgálata, PEME konference–XVII PhD conference of Professors Association for European Hungary, ISBN number: ISBN 978 615 5709 05 0, pp.167-173 (full paper)

Tóth, V. Zs., Jung A. (2021). Algae investigation of Lake Balaton with Sentinel, Deutschne Gesellschaft für

Photogrammetrie, Fernerkundung und Geoinformation éves nemzetközi konferencia, Stuttgart, Németország

Tóth V.Zs, Jung A. (2021). Investigation of algae in lakes supported by remote sensing methods, 10th Algal Biomass, Biofuels and Bioproducts Conference, Waikola, Hawaii

Tóth, V. Zs., Jung A. (2021). A Balatoni algásodás távérzékeléses vizsgálata, X. Hungarian Geography Magyar Conference ISBN 978-615-01-2899-3 (abstract)

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