Satellite data for monitoring and management support of small lake water quality

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Highlights

- High correlation between seasonally aggregated Sentinel-2 Data and lake trophic states.
- Automatable single pixel time series analysis.
- Seasonal ranking of lake water quality.

Introduction

Small water bodies fulfill important ecological functions and deliver ecosystem services in urban areas (Costadone, 2021). They contribute to biodiversity (Oertli and Parris, 2019), they are a place of recreation for residents, thus increasing the quality of life in a city, and they have a cooling effect (Cheval et al., 2020), which is becoming increasingly important in times of rising heatwaves as a result of climate change. However, they are also subject to many influences that can have a negative impact on water quality. In contrast to large water bodies, lakes with a size of less than 50 hectares are not subject to obligatory monitoring according to the Water Framework Directive, and therefore receive significantly less attention. They are primarily of local importance and are therefore often not monitored and managed centrally. This often leads to a lack of knowledge. Due to the large number of water bodies, continuous limnological monitoring requires considerable financial and human resources and is often not feasible. In Berlin alone, there are over 400 small lakes that are affected by nutrient and pollutant inputs and are more frequently drying out as a result of prolonged droughts in summer. Alternative monitoring to support the management of lakes is therefore urgently needed.

At the same time, more and more environmental data is being collected. The EU Horizon project AD4GD aims to develop a Green Deal data space for different types of data that can be used to solve environmental problems. The F.A.I.R. principles will be applied: Data must be findable, accessible, interoperable and reproducible. This includes remote sensing data that has been collected for some time by NASA (e.g. Landsat mission) and ESA (e.g. Sentinel mission). In addition, there are a growing number of providers of high-resolution satellite imagery. The first satellite in ESA's Sentinel-2 mission was launched in 2015 and will be joined in 2017 by a second satellite of the same design, which uses a multispectral instrument to measure the reflectance of specific wavelengths in the visible and near-infrared spectrum. ESA's Copernicus program provides water quality services using Sentinel-2 data. Many other approaches are already in use to estimate water quality using remote sensing data. For example, satellite data can be used to estimate chlorophyll-a and turbidity in large lakes (Yang et al., 2022).

To obtain reliable estimates, many pixels of a lake are usually spatially averaged. The resolution of the Sentinel-2 data is between 10 and 60 metres, depending on the wavelength, and can therefore be used to a limited extent for small lakes. However, spatial averaging is hardly possible as only a few pixels are available. Therefore, instead of spatial averaging, a method has been developed where a pixel can be averaged over time to provide information on the trophic state of lakes. The aim is not to describe water quality parameters at one point in time, but to estimate the trophic index as a limnological sum parameter. The method presented is a first step towards using satellite data to describe small lakes, which will be further adapted and optimised during the course of the project.

Methodology

The method was developed on 16 large lakes around Berlin in Brandenburg, Germany, with trophic indices ranging from 1.4 to 4.6, and thus including oligotrophic to polytrophic surface waters. The trophic data are from 2016, which is the most recent data available online for most of the Brandenburg lakes (LfU, 2023). Although the method will eventually be developed for monitoring small lakes in Berlin, it was calibrated on large lakes due to the better database. The transferability of the method will be tested during the AD4GD project.

Water quality data

There are various trophic state evaluations that describe the nutrient balance and biomass production of lakes. In Brandenburg, the trophic index according to LAWA is used (LAWA, 2014), which is based on Carlson et al. (1977). The trophic index uses classification formulae for the parameters chlorophyll-a, Secchi disk transparency and total phosphorus (seasonal mean and spring value), which were already identified as the most suitable trophic parameters in a global OECD study (1982). A season ranges from March to November.

Retrieve and process Sentinel-2 Data

The Sentinel-2 Level-2 data (https://sentinel.esa.int/web/sentinel/user-guides/sentinel-2-msi/processing-levels/level-2) were downloaded as a time series of a pixel in the lake using the Google Earth Engine. Satellite data from 2018 was used for the present analysis, as this was the first year in which two satellites were deployed in the Sentinel-2 programme and the waters were therefore overflown every 5 days.
Only cloud-free pixels were used for further analysis. Specifically, this means that all pixels with a *cloud mask index* of 0 were used where there was also a *cloud probability* of less than 5 %. Both the *cloud mask index* and the *cloud probability* are provided within the Sentinel-2 product. Bands 1 to 6 were then normalised so that the band with the highest reflection is 1 and the band with the lowest reflection is 0 at any given time.

Table 1. Used wavelength of Sentinel-2 mission

	Central wavelength [nm]
Band 1	443
Band 2	490
Band 3	560
Band 4	665
Band 5	705
Band 6	740

The normalised bands were then used to calculate a centroid reflection per time point, considering the fact that nutrient-rich waters tend to have higher chlorophyll-a content and greater turbidity and therefore reflect higher wavelengths than nutrient-poor waters (Copernicus, 2020). The centroid reflection wavelength (from here on referred to as CRW) is the weighted average wavelength that is reflected and can be calculated by:

$$\lambda_{center} = \frac{\sum \lambda_i \times R_i}{6}$$

where λ is the wavelength of the Bands 1 to 6 in nm and R is the normalised reflection of the corresponding wavelength.
The observation period was chosen to be similar to that of the trophic index, from March to November of a year. The CRWs were used to calculate monthly averages, which were then combined to form the annual average. This ensured that all months were equally included in the overall analysis, even if they contained different numbers of cloud-free pixels.

Results and discussion

All results refer to the CRW, which is an abstract aggregation of reflection intensity from satellite data. The parameter itself is difficult to interpret, but can be used to compare water colour in time or space. Figure 1 shows the relationship between the annual CRW and the trophic index of the 16 selected lakes. The coefficient of determination of the regression is 0.86, indicating a strong correlation. Although the trophic status (2016) and the satellite data (2018) are from different years, the ranking of the lakes is very similar for both parameters. This can be achieved for large lakes using only one pixel of the water body. Based on these findings, it seems to be possible to directly use the CRW to determine the trophic state of the lake.

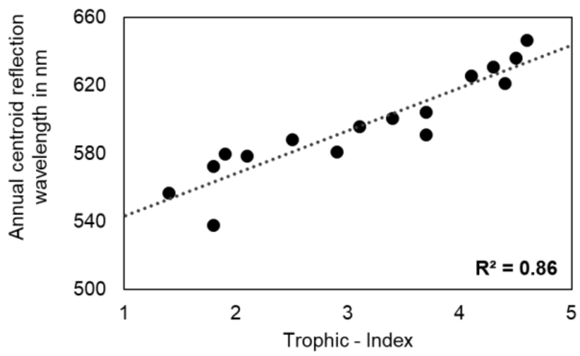

Figure 1. Correlation between annual average of the weighted reflected wavelength and the trophic index of 16 lakes in Brandenburg, Germany.

Figure 2a shows the time course of the annual CRW, which is by no means constant. It fluctuates between years, although the constellation between the displayed lakes changes only slightly (Figure 2b). For a total of 13 of the 16 lakes analysed, the CRW of 2018 is higher than that of the following years. The year 2018 was an exceptionally hot year in Brandenburg with a significant deficit in the water balance (LfU, 2022). This suggests that environmental conditions can have a strong influence on the CRW. Although water bodies can be compared within a period of time, for temporal trends environmental conditions must be included in the assessment.

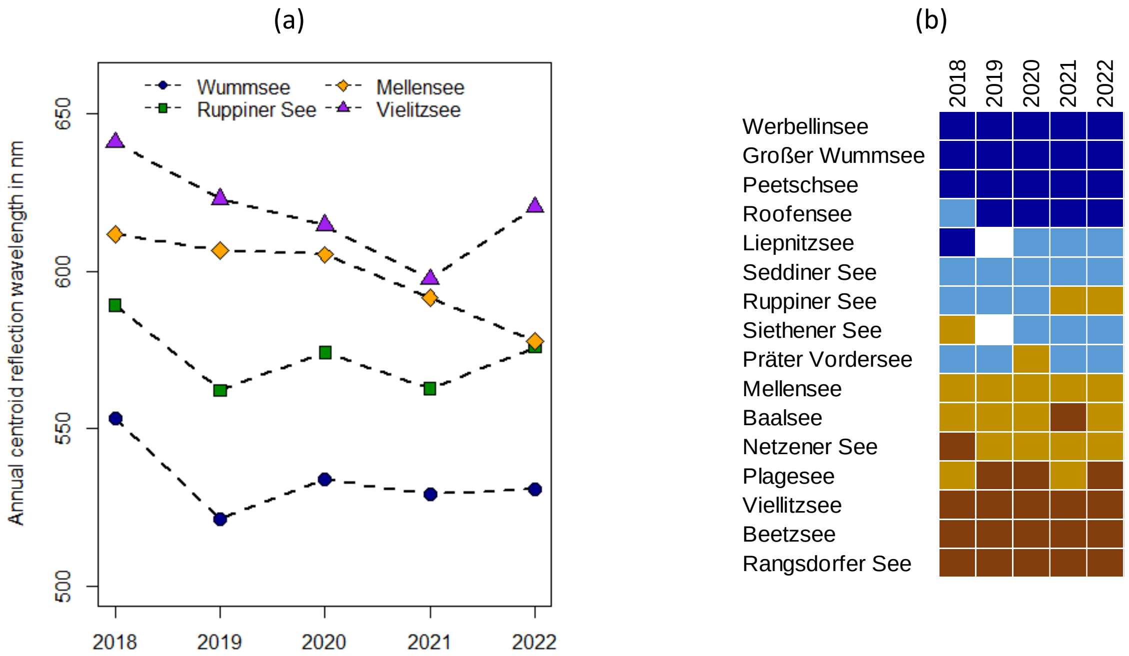

Figure 2. Temporal dynamic of the the CRW (a) four example lakes in Brandenburg, Germany, and (b) the effects on lake water quality ranking between 2018 and 2022. (classified into 25 % quantiles. dark blue: best relative water quality, light blue: good relative water quality, light brown: bad relative water quality, dark brown: worst relative water quality, white: no data available)

Whether the trophic index varies to the same extent between the years could not be tested for the Brandenburg lakes, as the trophic index is not determined annually. Further research is needed here. Figure

2a further shows that the CRW of Mellensee continues to decrease in 2022, contrary to the trend for all other lakes. As all lakes were exposed to roughly the same environmental conditions, this could be an indication that the nutrient situation in the lake is actually improving. On the contrary the Ruppiner See water quality decreases compared to the other lakes in 2022. Including the surrounding water bodies allows for trend analysis of the water quality.

Conclusions and future work

The paper shows a very high correlation between the CRW and the trophic index. The method is based only on Sentinel-2 Level-2 data and can be easily automated. However, the CRW is an abstract value and may not be translatable one-to-one into limnological parameters. The method can be used to assess water quality in three ways: (i) to compare lakes in the same season and thus rank lakes according to their trophic status, (ii) to identify trends in the trophic status of a water body over a long time period, allowing the identification of needs for action and the evaluation of nutrient reduction measures, and (iii) to assess the homogeneity of water quality within a lake by looking at individual pixels.
Further investigations within the AD4GD project will benchmark the CRW against alternative candidate spectral summaries and will extend the validation of the method to larger and contemporaneous datasets. In addition, it will be investigated what conclusions can be drawn from shorter time periods, e.g. monthly averages.

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