Evaluation of the performance of Pléiades Neo and Sentinel-2 Satellite Imagery for Chlorophyll-a Detection

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Abstract

Assessing chlorophyll-a (Chla), which is an indicator of algal biomass, is important for monitoring water quality and protecting natural resources. Today's technology enables the acquisition of high-resolution satellite imagery allowing for detailed observation of Chla levels even in small scaled water bodies such as ponds. In this study, the spatial distribution of Chla in a pond located at the Istanbul Technical University (ITU) Campus with an area of about 1.9 ha was assessed by using both high-resolution (Pléiades Neo) and medium-resolution (Sentinel-2) satellite imagery, along with in situ measurements. Pléiades Neo and Sentinel-2 and satellite images were acquired on June 10 and 11, 2024. Normalized Difference Chlorophyll Index (NDCI) was applied to images to determine Chla levels in the pond. Linear regression analysis was performed to retrieve Chla concentration values from NDCI values. The results showed that Chla concentrations ranged 16.38 - 23.83 mg/m³ based on in situ measurements, 16.52 -23.75 mg/m³ based on Pléiades Neo data and 15.49 - 23.74 mg/m³ based on Sentinel-2 data. Both Pléiades Neo and Sentinel-2 data were consistent with in situ Chla measurements. Using high-resolution Pléiades Neo imagery, the detailed spatial distribution of Chla was determined. Based on the satellite data, higher Chla concentrations on the southern and southwestern shores of the pond. This research presents a practical approach for evaluating Chla levels within ponds, leveraging medium- and very high-resolution satellite images and the methodology can be used for water quality monitoring in small scale aquatic environments.

1. Introduction

The preservation of water quality has emerged as a critical priority worldwide due to the growing demand for clean water access. Preserving water quality in an effective way necessitates continuous monitoring, with water quality parameters providing valuable insights into its eutrophic condition. One of the key water quality parameters, chlorophyll-a (Chla), a pigment used as an indicator of algae, is a crucial biological indicator of primary productivity in a waterbody. In addition, it is a critical parameter to assess the level of eutrophication as it is highly correlated with nutrient concentrations and algal biomass (Gholizadeh et al., 2016). Thus, Chla is crucial for understanding the overall ecological condition of water bodies.

Ground-based in-situ measurements are one of the ways to assess Chla concentrations (Kuha et.al., 2020). While conventional methods provide accurate Chla assessments, ground-based measurements are time demanding, costly, and most importantly limited in spatial coverage. Chla, an effective indicator for phytoplankton biomass in lakes, is one of the spectrally active water quality parameters, it can be effectively detected using satellite imagery (Buma and Lee, 2020). With the rapid advancement of remote sensing technology, satellite sensors such as Landsat, and Sentinel satellite images are widely used for water surface monitoring (Tuzcu Kokal et al., 2023). Compared to ground-based monitoring methods, remote sensing techniques offer the advantage of providing continuous spectral and spatial information over large areas. Therefore, integrating ground-based measurements with satellite data can significantly improve the accuracy of Chla determination (Kayastha et.al., 2022; Yang et al., 2024).

Medium and low spatial resolution satellite images have been extensively used in the literature for assessing Chla levels in water bodies. Given that phytoplankton affect the optical properties of water, the blue-green band ratio (BR) is widely regarded as one of the most commonly used empirical method for assessing Chla concentration, as demonstrated in studies of lakes in Wales (George and Malthus, 2001) and in the Sea of Marmara (Tuzcu Kokal and Musaoğlu, 2021). Moses et al. (2009) applied two-band and three-band models using red and near-infrared bands to Medium Resolution Imaging Spectrometer (MERIS) images to detect Chla and observed their suitability for predicting Chla in turbid productive waters. Ambrose-Igho et al., (2021) applied various algorithms like band ratios and the Maximum Chlorophyll Index to Sentinel-2 data, demonstrating its appropriateness for assessing different water quality parameters including Chla in small, low-turbidity lakes in Illinois State (U.S.A).

Advancements in space technologies have greatly facilitated the access to high-resolution satellite imagery, which is particularly essential for effectively monitoring coastal areas and water bodies (Tuzcu Kokal et al., 2022). As an example, Mortula et al., (2020) used high-spatial-resolution WorldView-2 data to assess Chla concentrations in Dubai Creek and observed a high correlation with in-situ measurements. Yigit Avdan et al. (2019), in another case study, used high-resolution RapidEye satellite imagery with a 5-meter spatial resolution to assess various water quality parameters in a small dam, observing a strong correlation between RapidEye-derived reflectance values and in-situ measurements.

Pléiades Neo 3 satellite, recently launched in 2021, provides very high-resolution (0.3 m; Table 1) imagery critical for generating detailed information in small ponds (Url-1). On the other hand, Sentinel-2 has offered freely available medium-resolution (10-60 m; Table 1) satellite images since 2015, enabling comprehensive water surface monitoring (Url-2). In this study, Pléiades Neo 3 and Sentinel-2 satellite imagery were utilized to assess Chla levels in the small pond, with an analysis conducted to compare the performance of each dataset.

2. Data and Methodology

2.1 Study Area

The pond located at the Istanbul Technical University (ITU) Campus (Istanbul, Türkiye), was selected as the pilot area. ITU pond has a maximum width of approximately 0.15 km and a maximum length of approximately 0.23 km and with an area of approximately 1.9 hectares (Figure 1). It is an artificial pond fed by rainwater (Url-3). The ecosystem of the pond is rich which consists fish, ducks, turtles and various bird species. The pond is surrounded by trees and there is a concrete walking path around the southern section of the pond (Figure 1).

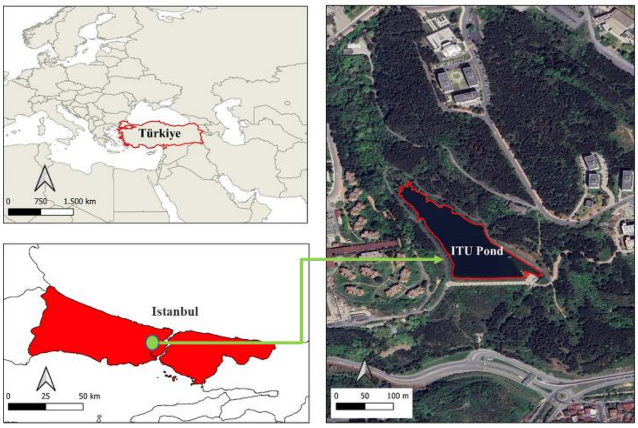

Figure 1. Geographical location of the study area (ITU pond). The upper-left panel depicts the location of Türkiye, while the lower-left panel indicates the location of Istanbul. The right panel presents the true color Pléiades Neo 3 satellite image of the study area, highlighting the delineated ITU pond boundaries.

2.2 Data Used

Within the scope of the study, satellite data and field measurements were used. Pléiades Neo and Sentinel-2 data were used to determine Chla from satellite data. The Sentinel-2 satellite provides freely accessible images with medium spatial resolution and high temporal resolution (SUHET, 2013). The Sentinel-2 image was downloaded from the Copernicus website (https://dataspace.copernicus.eu/) (Url-4). Pléiades Neo data provides commercially available very high spatial resolution satellite images (0.3 m) (Url-5). The specifications for both datasets are provided in Table 1 (Url-5; Url-6; SUHET, 2013). Due to the effectiveness of red and red-edge bands in Chla detection through satellite imagery (Mishra and Mishra, 2012), the red and red-edge spectral bands from both satellite datasets were used for analysis. These specific bands used are emphasized in bold in Table 1.

Sentinel-2 – 10.06.2024			
Band Number	Band Name	Wavelength (μm)	Spatial resolution (m)
1	Coastal and Aerosol	0.433 – 0.453	60
2	Blue	0.458 – 0.523	10
3	Green	0.543 – 0.578	10
4	**Red**	**0.650 – 0.680**	**10**
5	Red Edge	0.698 – 0.713	20
6	**Red Edge**	**0.733 – 0.748**	**20**
7	Red Edge	0.773 – 0.793	20
8	NIR	0.785 – 0.900	10
8A	Red Edge	0.855 – 0.875	20
9	Water vapor	0.935 – 0.955	60
10	Cirrus	1.360 – 1.390	60
11	SWIR	1.565 – 1.655	20
12	SWIR	2.100 – 2.280	20
Temporal Resolution = 5 days			
Pléiades Neo – 11.06.2024			
1	**Red**	**0.620 – 0.690**	**0.3**
2	Green	0.530 – 0.590	0.3
3	Blue	0.450 – 0.520	0.3
4	NIR	0.770 – 0.880	0.3
5	**Red Edge**	**0.700 – 0.750**	**0.3**
6	Deep Blue	0.400 – 0.450	0.3
Temporal Resolution = Two times per day			

Table 1. Characteristics of Sentinel-2 and Pléiades Neo satellites.

Spectroradiometer measurements were made at 5 points and Chla measurements were made at 2 points within the scope of field studies (Figure 2). Spectroradiometer measurements and sampling for Chla were performed on June 11, 2024, coinciding with the acquisition date of Pléiades Neo. Since they were simultaneous, the reflectance values obtained from the spectroradiometer were compared with the reflectance values obtained from the Pléiades Neo. The FieldSpec HH spectroradiometer with a spectral range of 325 - 1075 nm was used. In this context, measurements were made at the 5 points as shown in the Figure 2.

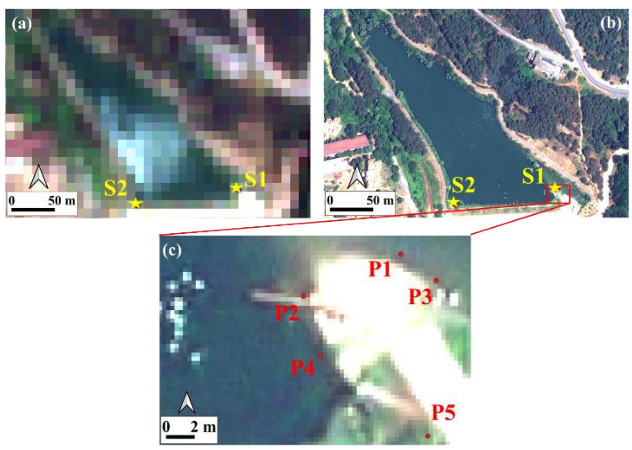

Figure 2. a) True-color Sentinel-2 satellite imagery; b) true-color Pléiades Neo 3 satellite imagery displaying water sampling station locations; c) locations of spectroradiometer measurements.

The spectral reflectance graphs corresponding to spectroradiometer measurements are presented in Figure 3. At point 5 (P5), the presence of pollution causes the reflectance to differ noticeably from that observed at the other four points. Since red and red edge bands were used for Chla determination, reflectances in red and red edge bands were highlighted in the graphs (Figure 3).

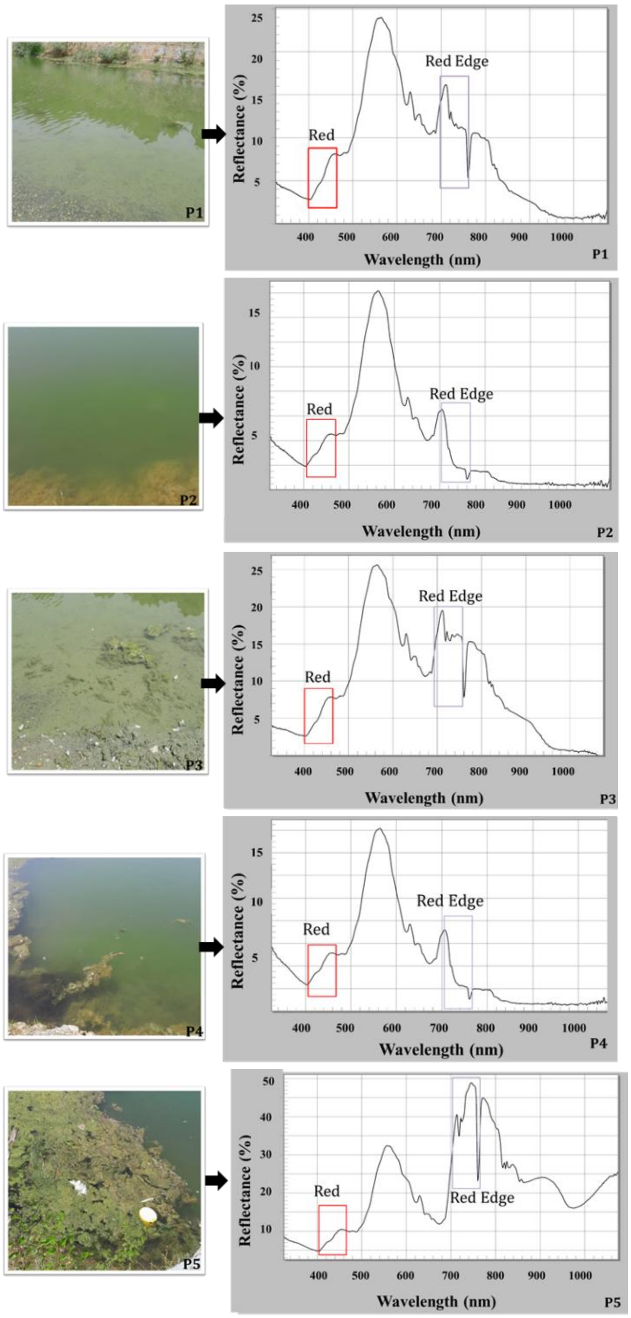

Figure 3. Spectral reflectance plots obtained from spectroradiometer measurements, along with in-situ photographs associated with each measurement points.

Samples for Chla were taken from two different stations of the pond. The locations of these two stations are shown in Figure 2. Chla concentrations in the pond water samples from S1 and S2 were determined spectrophotometrically by following standart APHA 10200 method (by 95% acetone filter pigment extraction), using an INESA 722 VIS spectrophotometer at the Biogeochemistry Laboratory at ITU. Table 2 shows the Chla values of these two stations. The Chla value in the first station (S1) was 16.38 mg/m^3 with a standard deviation of 3.23 mg/m^3 and the Chla value in the second station (S2) was 23.83 mg/m^3 with a standard deviation of 3.83 mg/m^3.

	Time (UTC+3)	Water Temperature (°C)	Chla (mg/m^3)	Std (mg/m^3)
S1	12:30	30.3	16.38	3.23
S2	12:41	33	23.83	3.83

Table 2. Chla measurement results at S1 and S2.

2.3 Methodology

The methodology applied in this study is illustrated in the work flow chart presented in Figure 4.

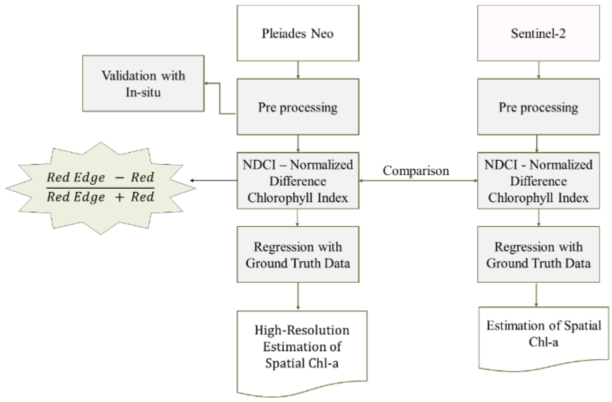

Figure 4. The work flow chart illustrating the applied methodology based on multispatial resolution satellite images.

As a first step, preprocessing was conducted on both the Pléiades Neo and Sentinel-2 data. Since the Pléiades Neo satellite overpass and the spectroradiometer measurements were conducted concurrently, the Pléiades Neo reflectance values were validated against in-situ spectroradiometer measurements. NDCI (Mishra and Mishra, 2012) was applied to the satellite imageries (Eq. 1) to detect Chla levels.

$$\text{NDCI} = \frac{\text{Red Edge} - \text{Red}}{\text{Red Edge} + \text{Red}} \tag{1}$$

For model calibration a linear regression analysis was performed between in-situ measurements from two stations (S1 and S2) and the corresponding surrounding pixels' NDCI values. The calibrated model was then applied to the satellite images to estimate Chla concentration values. The results obtained from very high- and medium- spatial resolution images were compared, and thematic maps showing Chla concentrations were generated.

3. Results and Conclusion

The red and red edge spectral bands were used while applying NDCI. Therefore, the reflectance values from Pléiades Neo were compared with the spectroradiometer measurements in red and red edge spectral bands to conduct validation. The validation between the Pléiades Neo and the in-situ spectroradiometer measurements were shown in Figure 5. Pléiades Neo and spectroradiometer measurements were found to be compatible. The coefficient of determination (R^2) between the Pléiades Neo satellite-derived reflectance values and the reflectance values obtained through in-situ spectroradiometer measurements was calculated to be 0.85 for the red band and 0.97 for the red edge band (Figure 5).

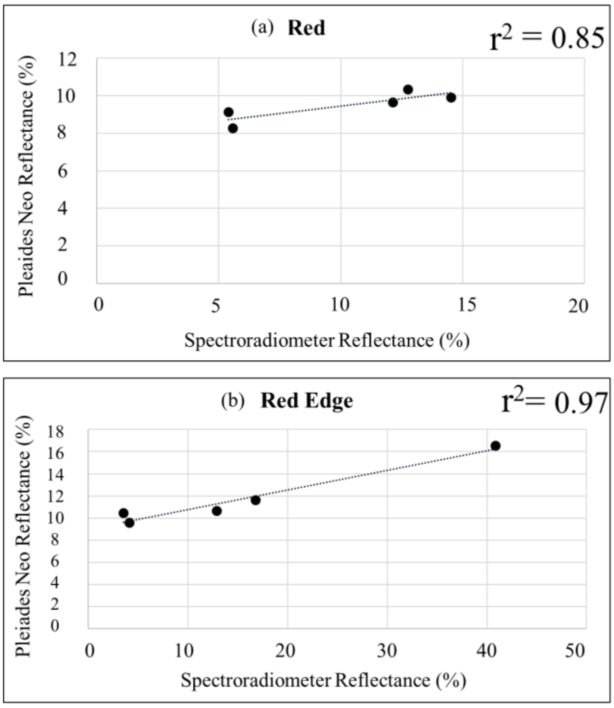

Figure 5. Validation of Pléiades Neo satellite image against in-situ spectroradiometer measurements in a) the red and b) red edge spectral bands.

Following the validation of reflectance values, the NDCI index was applied to both satellite images. Thereafter, a linear regression model was calibrated by using NDCI values and in-situ Chla measurements to accurately estimate Chla concentrations in the pond. In the regression analysis, the central pixels and neighboring pixels around each station point (S1 and S2) were considered. In the calibration stage, the linear model coefficients (Pléiades Neo: p_1= 70.26, p_2= 11.25; Sentinel-2: p_1= 83.41, p_2= 8.729) obtained from this regression were used to obtain Chla concentration values from NDCI values. For Pléiades Neo and Sentinel-2 data, the R^2 values derived from the model regression are 0.99 and 0.97, respectively. Equation of the linear model was given in Eq. 2.

$$\text{Chla} = p_1 * \text{NDCI} + p_2 \quad (2)$$

After applying the calibrated model, Chla maps were generated using Pléiades Neo (Figure 6.b) and Sentinel-2 images (Figure 6.a). As illustrated in Figure 6.b, Chla concentrations were observed to be increased in the pond's southern and southeastern coastal region. This increased Chla in the southern region was further verified by an in-situ photograph taken at the P5 point location (Figure 3). On the other hand, increased Chla values along the coastal areas, including the southern and northern sections, were observed in the Chla map derived from the Sentinel-2 image (Figure 6.a). The higher Chla concentrations observed at the land-lake interface are likely due to mixed pixels containing both terrestrial and aquatic features.

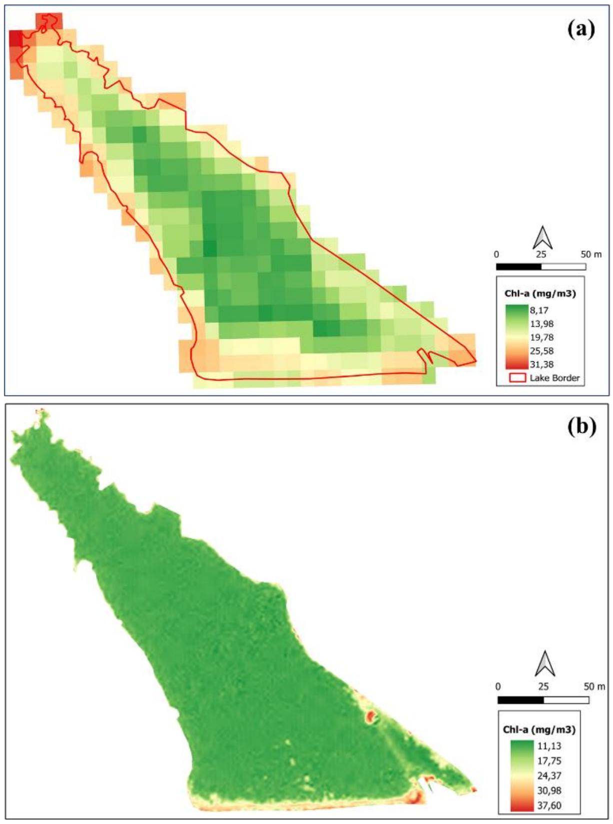

Figure 6. Thematic map of Chla distribution retrieved from a) the Sentinel-2 image and b) Pléiades Neo image.

The measured Chla values in the sampling points S1 and S2 were compared with the Chla values obtained from Sentinel-2 and Pléiades Neo data. Field measurements of Chla showed a higher consistency with Chla values in Pléiades Neo images compared to Sentinel-2 images due to the higher spatial resolution of Pléiades Neo. Field measurements at S1 and S2 confirm that Chla levels at S1 are lower than at S2, aligning with both Pléiades Neo and Sentinel-2 data results. While the Chla levels obtained from in situ measurements at points S1 and S2 were 16.38 mg/m³ and 23.83 mg/m³, respectively, the Chla levels obtained from Pléiades Neo were 16.52 mg/m³ and 23.75 mg/m³, respectively. Additionally, the Chla levels obtained from Sentinel-2 were 15.49 mg/m³ and 23.74 mg/m³, respectively.

Pléiades Neo's high spatial resolution allows for greater detail in the imagery, provides more accurate and sensitive Chla measurements. On the other hand, Sentinel-2 images provide freely accessible temporal data, presenting a potential advantage for future monitoring of the ITU pond through satellite-based time series analysis. In addition, higher number of field measurements would further validate the results obtained from Pléiades Neo and Sentinel-2 data.

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