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Measurements of chlorophyll content in freshwater phytoplankton

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Abstract

This study investigates eutrophication in Kraków's urban freshwater bodies by analysing *chlorophyll-α* concentrations, which indicate phytoplankton biomass. We measured *chlorophyll-α* using fluorescence in four lakes: Staw Płaszowski, Zalew Nowohucki, the pond in Park Lotników, and Staw Dąbski and applied the Trophic State Index (TSI) to evaluate their eutrophication levels. Staw Płaszowski showed stable, low *chlorophyll-α* levels, suggesting resistance to significant phytoplankton blooms. In contrast, Zalew Nowohucki exhibited notable *chlorophyll-α* fluctuations and peaks, indicating variable conditions and nutrient inputs. The pond in Park Lotników and Staw Dąbski also displayed variability with rapid *chlorophyll-α* peaks, indicating increased susceptibility to eutrophication. Cyanobacteria content varied, no cyanobacterial blooms reached critical levels. TSI classifications were: Staw Płaszowski as mesotrophic, Zalew Nowohucki as eutrophic, and the pond in Park Lotników as mesotrophic. Staw Dąbski showed seasonal fluctuations between mesotrophic and eutrophic states. Effective management requires a comprehensive approach, integrating multiple environmental factors and extensive sampling. Future research should focus on long-term monitoring and broader watershed considerations, including urban lakes, for effective eutrophication management.

Keywords: phytoplankton, chlorophyll-α, eutrophication, cyanobacteria, urban lakes

1. Introduction

In today's world, aquatic ecosystems are particularly vulnerable to anthropogenic threats that disrupt the biochemical balance of water bodies. One of the most significant manifestations of this disruption is eutrophication, which is "the enrichment of water with nutrients, particularly nitrogen and phosphorus compounds, which accelerate the growth of algae and other higher forms of plant life, leading to undesirable disruption of biological water relations and deterioration of water quality" (Ustawa z dnia 20 lipca 2017 r.). Recognized as a hallmark of the Anthropocene (Chang et al., 2022), eutrophication poses a severe threat to the quality of both inland and coastal waters (Soszka, 2009).

Eutrophication is already recognized as a significant problem in Europe, with projections indicating a 13-28% increase in nutrient transport to European seas by 2050. By then, 42% of Europe's population will be within reach of the ten most polluted rivers by nitrogen and phosphorus (Ural-Janssen et al., 2024). A key indicator of eutrophication is the increased biomass of phytoplankton.

Phytoplankton forms the basis of the aquatic food web, drive geochemical processes, and determine the existence of other living organisms (Murkowski & Prokowski, 2003; Zheng & DiGiacomo, 2017). It encompasses various groups including green algae, red algae, yellow-green algae, cyanobacteria, diatoms, and dinoflagellates (Johan et al., 2018). Nonetheless, the over-fertilization of aquatic ecosystems can precipitate a rapid increase in phytoplankton abundance, commonly referred to as phytoplankton blooms. During such blooms, the population of zooplankton, which are the primary consumers of phytoplankton, often cannot keep pace with the proliferating phytoplankton. This imbalance can result in a deficiency of dissolved oxygen, caused by the microbial decomposition of the unconsumed biomass of dead phytoplankton (Murkowski & Prokowski, 2003). Additionally, excessive phytoplankton can adversely affect aquatic plant life through the mechanism of shading (Scheffer et al., 1993).

Furthermore, an increase in phytoplankton content often signifies a rise in cyanobacteria levels, as cyanobacteria are a component of phytoplankton. In the 1990s, instances were recorded where cyanobacteria accounted for as much as 90% of the phytoplankton population (Krienitz et al., 1996). This dominance of cyanobacteria over eukaryotic phytoplankton is attributable to global warming and the excessive discharge of nutrients (Sukenik et al., 2015; Paerl & Huisman, 2008). Cyanobacteria, the unicellular photosynthetic bacteria, rank among the oldest organisms on Earth (Castenholz, 2015). They are known for their detrimental impacts, including the release of cyanotoxins, oxygen supersaturation in the upper layers of water bodies, and the transient depletion of oxygen at the bottom of these water bodies (Dondajewska et al., 2020). The frequency of cyanobacteria blooms, linked to eutrophication and climate change, has risen globally (Monchamp et al., 2018; Wilk-Woźniak et al., 2024).

Phytoplankton cells contain various forms of chlorophyll, with *chlorophyll*-α being a common measure of phytoplankton biomass and an indicator of eutrophication (Wang et al., 2012). *Chlorophyll*-α is a pervasive photosynthetic pigment found in all algae and plant cells (Zheng & DiGiacomo, 2017; Stoń-Egiert, 2024).

Chlorophyll-α concentration can be measured using various methods, including spectrophotometry, high-performance liquid chromatography (HPLC), fluorescence, and remote sensing via satellite platforms (Johan et al., 2018; Zheng & DiGiacomo, 2017; Wang et al., 2012). In this study, a fluorescence-based device was used due to its speed, minimal sample preparation, accuracy, and reduced susceptibility to human error.

To estimate the trophic status of the studied lakes based on *chlorophyll*-α concentrations, we employed the Trophic State Index (TSI), originally introduced by Carlson in 1977. This index helps determine whether a lake is

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hypereutrophic, eutrophic, meso-eutrophic, mesotrophic, or oligotrophic (Carlson, 2007). The TSI scale ranges from 0 to 100, with higher values indicating greater eutrophication and, consequently, higher biological productivity (Carlson, 1977; Fuller & Minnerick, 2008).

While research on chlorophyll content has predominantly focused on marine and coastal environments, eutrophication also represents a significant threat to inland water bodies, including recreational and natural lakes, fisheries, and drinking water sources (Paerl, 1988; Carpenter et al., 1998). This study examines chlorophyll content in freshwater phytoplankton using water samples collected from four lakes in Kraków, one of Poland's largest cities. The selected water bodies are located in close proximity but differ in depth, surface area, trophic status, and time of formation. This allows for assessment of whether algal blooms occur simultaneously across these lakes in response to weather conditions or are driven by other factors.

Understanding eutrophication is important for developing effective mitigation strategies and shaping urban policies. This research focuses on urban freshwater bodies, offering a detailed look at the local impacts of eutrophication and contributing to broader environmental management strategies. By analyzing the causes and effects of eutrophication in Kraków's lakes, the study aims to devise targeted approaches for mitigating the issue and enhancing water quality.

2. Materials and Methods

2.1. Research area

The study was conducted in Kraków, Poland, focusing on four distinct water bodies: Staw Płaszowski (Płaszow Pond), Zalew Nowohucki (Nowohucki Reservoir), the pond in Park Lotników, and Staw Dąbski (Dąbski Pond) (Fig. 1). Each site represents a unique freshwater ecosystem characterized by varying levels of human impact and eutrophication status.

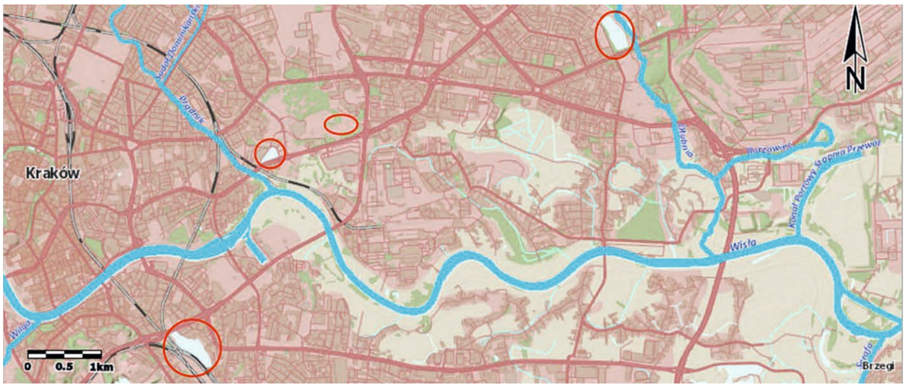

Fig. 1. Location of the studied water bodies (indicated by red frames) in the eastern part of the city of Kraków, along with the main watercourses (hydroportal, ISOK, 2024)

2.1.1. Staw Płaszowski

Spanning 9.0 hectares (Eggenbauer et al., 2016), Staw Płaszowski is located in the Płaszów district, northeast of Kraków. Originally formed from gravel and clay pits used in railroad construction (Pietrzyk-Sokulska, 2010; Zachariasz & Porada, 2019). The lake is bordered by a busy street to the northeast and residential and commercial areas to the east and west. The lake belongs to the Vistula River basin (hydroportal, ISOK, 2024).

The reservoir is surrounded by deciduous trees, with its banks overgrown by reeds and bulrush (Ogar, 2016). A diverse array of 37 bird species has been observed. The invertebrate fauna is equally rich, particularly insects with larvae inhabiting aquatic environments, featuring 24 dragonfly species (Zachariasz & Porada, 2019). Fish species found in the reservoir include silver carp, carp, pike, perch, tench, rudd, roach, and bream (Ogar, 2016).

The sampling location was in the southwestern part of the lake, approximately at 50°02'21.4"N 19°58'26.9"E. Surrounding the sampling point, there is a lush landscape of greenery and coastal vegetation, highlighting the natural biodiversity and ecological significance of the area (Fig. 2).

Fig. 2. Staw Płaszowski a) sampling site; b) new footpaths and a lake overview (photo: Agnieszka Chechelska)

2.1.2. Zalew Nowohucki

Located in the Bieńczyce District, east of Kraków, Zalew Nowohucki was created in 1952 primarily for recreational use and to mitigate pollution from nearby steelworks (Mundała et al., 2016; Wolny-Koładka, 2016). Spanning 7 hectares, the reservoir is fed by the Młynówka River and situated within the Dłubnia River basin (Mundała et al., 2016) and is stocked for fishing (Zachariasz & Porada, 2019). An artificial island, approximately 0.15 hectares in size, is positioned in the reservoir's centre (Mundała et al., 2016). The reservoir supports various bird species, including mute swans, mallards, coots, and terns, which nest on the islands (Zachariasz & Porada, 2019).

The sampling point on the west side of the reservoir (approximately 50°04'43.0"N 20°03'04.6"E) offers views of the serene natural surroundings (Fig. 3).

Fig. 3. Zalew Nowohucki a) sampling site; b) a lake overview (photo: Agnieszka Chechelska)

2.1.3. Pond in Park Lotników

Located in the Czyżyny district to the west of Kraków, this pond is a recent addition to the city's water bodies and is currently in the early stages of biological development. The pond is predominantly surrounded by deciduous trees, including weeping willows nearby (Fig. 4). In the coastal zone, narrow-leaved clubmoss is present, while the water zone features yellow water lilies and duckweed. Some of these plants were artificially introduced during the year preceding the survey.

Fig. 4. Pond in Park Lotników a) sampling site; b) a pond overview (photo: Agnieszka Chechelska)

The pond is part of the Wisła River basin (hydroportal, ISOK, 2024) and is conveniently located near the Tauron Arena, surrounded by a network of walking paths, bridges, and a restaurant. Despite its urban setting, the pond serves as a tranquil retreat for visitors amidst the bustling activities of Kraków. Approximately 100 meters south of the pond runs Aleja Pokoju, a busy road lined with a mall.

The sampling point is positioned on the southern edge of the pond (approximately at 50°04'00.1"N 19°59'47.0"E) (Fig. 4).

2.1.4. Staw Dąbski

Located approximately 700 meters east of the Pond in Park Lotników, Staw Dąbski spans 2.1 hectares and was formed through clay excavations for a brickyard in the 1930s (Bąk et al., 2017; Eggenbauer et al., 2016). The reservoir and its surroundings support a diverse flora, with over 170 species of vascular plants. It also hosts a variety of aquatic life, nine fish species inhabit the reservoir, including the protected roseate (Waszkiewicz, 2000).

The pond serves as a habitat for numerous water and marsh birds (Waszkiewicz, 2000). It is also protected under Polish law and designated as an ecological utility by the Krakow City Council through a resolution on January 13, 2010. This protection aims to preserve the reservoir's ecosystem

Fig. 5. Staw Dąbski a) sampling site; b) swans inhabiting the lake (photo: Agnieszka Chechelska)

as a vital habitat for protected and endangered plant and animal species (Uchwała NR XC/1202/10 Rady Miasta Krakowa).

Nestled in the Grzegórzki district and part of the Wisła river basin (hydroportal, ISOK, 2024), Staw Dąbski has a designated sampling point on its eastern side, approximately at coordinates 50°03'54.6"N 19°59'13.4"E (Fig. 5).

2.2. Field work

Samples were collected weekly at dawn from April 11, 2024, to July 4, 2024. They were taken from the subsurface layer (20 cm depth) of water whenever possible, aiming to collect at the same spot consistently. Samples were preserved in thermoses to minimize temperature fluctuations, with thermoses pre-washed using distilled water and rinsed with water from the sampling site to avoid contamination. Analysis of samples was conducted within 8 hours to prevent degradation.

2.3. Laboratory analysis

Chlorophyll-α, cyanobacteria, and water turbidity were analysed using Moldanke's bbe Algae Torch chlorophyll probe, which utilizes fluorescence to measure phytoplankton and cyanobacteria concentrations. The probe employs 7 LEDs emitting light at 470 nm, 525 nm, and 610 nm. The pigments absorb this light and re-emit it at longer wavelengths, enabling quantification of algae concentrations in the water. The instrument underwent a calibration procedure as prescribed by the manufacturer.

2.4. Statistical analysis

Statistical analyses were conducted using R+RStudio software. Initially, the mean of three measurements per sample was computed. Subsequently, the Shapiro-Wilk test was conducted to assess the normality of data distributions at each sampling location. Given that most data did not follow a normal distribution and exhibited non-linear correlations, Kendall's correlation analysis was then employed to explore relationships within the study population.

As phytoplankton blooms are associated with elevated *chlorophyll*-α concentrations, conventional outlier detection methods are not suitable for this dataset. Therefore, outliers in the *chlorophyll*-α time series for Staw Dąbski were identified using the tsclean function from the *forecast* package in R. This approach detects anomalous observations based on the temporal structure of the data and replaces them through interpolation using neighboring values.

2.5. Calculation of trophic state index (TSI)

The Trophic State Index (TSI) was calculated using a model presented by Carlson (1977). This model allows for TSI calculation based on Secchi disk transparency, chlorophyll concentration, total phosphorus, or a combination of these factors. In this study, the equation involving chlorophyll content was used:

$$\mathrm{TSI}(Chl) = 10\left(6 - \frac{2.04 - 0.68\ln Chl}{\ln 2}\right)$$

where *Chl* is the *chlorophyll*-α content in mg/m^3.

While there have been concerns about calculating TSI based solely on chlorophyll content due to its variability with environmental conditions and nutrient supply, it is argued that this method potentially introduces fewer errors compared to using total phosphorus, total nitrogen, or Secchi disk depth (Carlson, 2007).

3. Results

3.1. *Chlorophyll-α* content

Chlorophyll-α levels in Staw Płaszowski remained relatively stable and low throughout the monitoring period (Fig. 6). Nowohucki exhibited notable variations in *chlorophyll-α* content throughout the season. Beginning with low levels in April, there was a sharp increase in early May, reaching nearly 60 μg/l by May 30th. This peak was followed by a further rise to approximately 75 μg/l on June 13th, before once more declining. The Pond in Park Lotników initially had moderate *chlorophyll-α* levels, with the highest average monthly concentration observed in June (Fig. 7). *Chlorophyll-α* content started off low but increased to about 20 μg/l by early May. Throughout June, the levels exhibited one peak, reaching a maximum of 36.5 μg/l on June 6th.

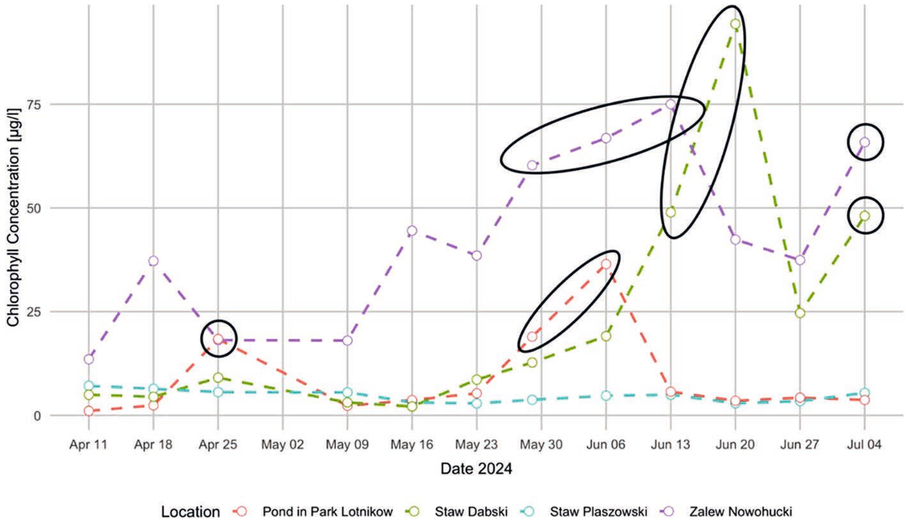

Fig. 6. *Chlorophyll-α* content in various water bodies over time of the study, with probable phytoplankton blooms outlined (black line) (own elaboration)

Staw Dąbski exhibited the most pronounced fluctuations among the four water bodies. *Chlorophyll-α* concentrations were initially low but increased sharply in early June, reaching nearly 95 μg/L by 20 June. Following a brief

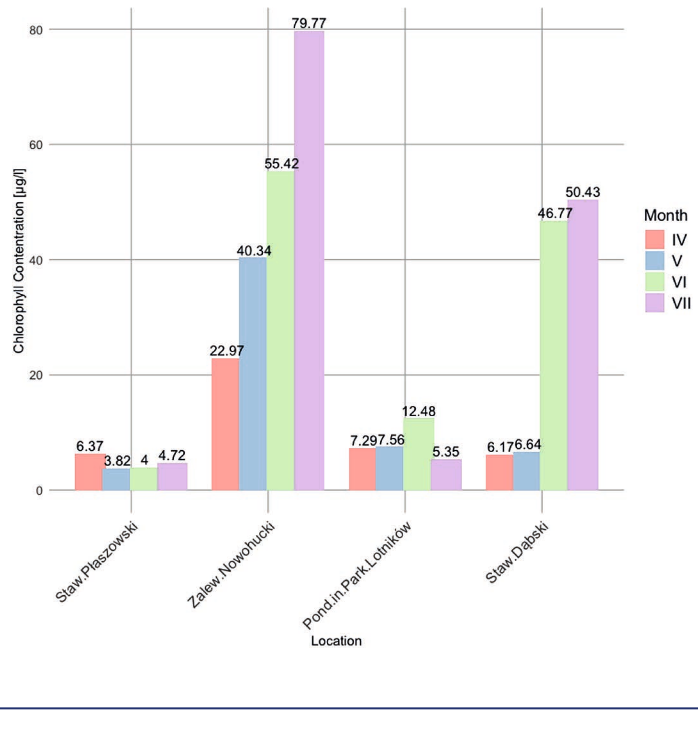

Fig. 7. Average *chlorophyll-α* content in different months in various water bodies (own elaboration)

decline, a second substantial peak occurred in early July, exceeding 45 μg/L. This variability is reflected in the monthly averages, with April and May values nearly eightfold lower than those observed in June and July (Fig. 7). No outliers were identified; the series cleaned using *tsclean* was identical to the original dataset, indicating that all observations were consistent with the expected temporal structure.

Probable phytoplankton blooms (Fig. 6) were estimated using the criterion that concentrations exceeding the median signify bloom initiation (Siegel et al., 2002). This criterion is supported by Longhurst (1988), who defines a bloom as an event characterized by an increase in biomass above normal levels.

The Shapiro-Wilk test indicated that two out of four *chlorophyll*-α data distributions were normal (p-*value* > 0.05). Consequently, Kendall's tau correlation was employed to assess relationships between *chlorophyll*-α content across different water bodies. A significant correlation (tau = 0.51) was found between Zalew Nowohucki and the Pond in Park Lotników throughout the study period.

When focusing on periods when the air temperature stabilized above 7°C, a strong correlation (tau = 0.64) was observed between Zalew Nowohucki and Staw Płaszowski. However, this correlation was not significant for the entire population (p-*value* = 0.031 > $\alpha/2$ = 0.025).

3.2. Cyanobacteria content, turbidity

Throughout the observed period, Zalew Nowohucki exhibits significant fluctuations in cyanobacteria content, with notable peaks around April 18, June 20, and July 4. This location shows the highest variability and the largest peaks compared to the other sites. In contrast, the Pond in Park Lotników experiences moderate fluctuations in cyanobacteria content. Although it generally stays below 2 μg/l, there are noticeable spikes, particularly around June 6. Staw Płaszowski maintains relatively stable and low cyanobacteria content throughout the period. The values mostly stay below 1 μg/l, with slight increases observed around June 13 and June 27. This location consistently shows the lowest cyanobacteria levels among the four sites. Staw Dąbski shows general stability, with some occasional spikes in cyanobacteria content. It peaks on May 23 and June 27. The fluctuations are more moderate compared to Zalew Nowohucki, but more pronounced than those in Staw Płaszowski. Overall, the data indicates that Zalew Nowohucki experiences the highest and most variable cyanobacteria content, while Staw Płaszowski has the most stable and lowest levels. Pond in Park Lotników and Staw Dąbski fall in between, showing moderate fluctuations with occasional peaks (Fig. 8).

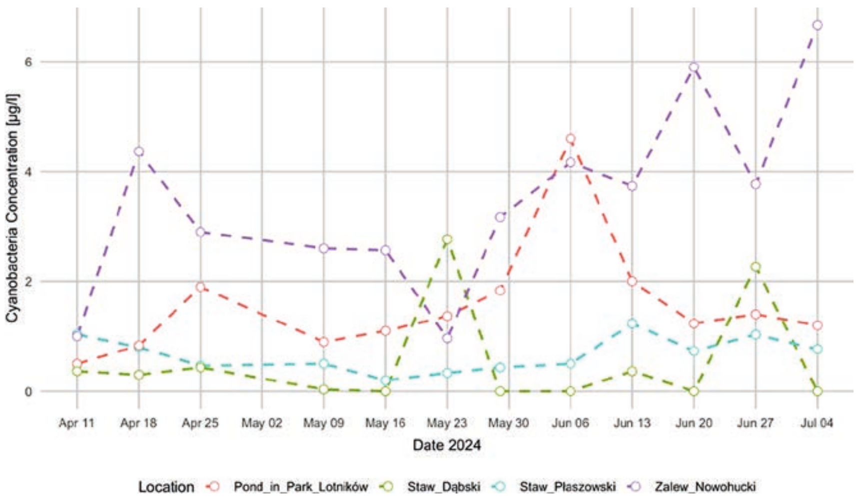

Fig. 8. Cyanobacteria content over time for four locations from April 11, 2024, to July 4, 2024 (own elaboration)

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Statistical analysis revealed a significant correlation between *chlorophyll-α* content and turbidity with the strongest correlation observed in Staw Płaszowski (tau = 0.62). Additionally, in the Pond in Park Lotników, there was a notable correlation between *chlorophyll-α* content and cyanobacteria levels (tau = 0.78).

3.3. Trophic state index

To estimate the trophic state of several lakes, the Trophic State Index (TSI) was calculated based on the *chlorophyll-α* content in each lake (Tab. 1). Given the nature of the data, which shows higher TSI values during phytoplankton blooms, the median was calculated to provide a measure of central tendency.

Table 1. Trophic state index calculated based on *chlorophyll-α* concentrations in studied lakes

Date	Staw Płaszowski	Zalew Nowohucki	Pond in Park Lotników	Staw Dąbski
11.04.2024	49,8	56,1	31,2	46,3
18.04.2024	48,8	66,1	39,2	45,3
25.04.2024	47,5	59,0	59,1	52,2
9.05.2024	47,4	58,9	38,7	41,7
16.05.2024	41,8	67,8	43,3	38,0
23.05.2024	40,9	66,4	46,9	51,7
29.05.2024	43,5	70,8	59,4	55,5
6.06.2024	45,8	71,8	65,9	59,5
13.06.2024	46,3	72,9	47,6	68,7
20.06.2024	41,0	67,3	42,9	75,2
27.06.2024	42,6	66,1	44,8	62,0
4.07.2024	47,1	71,6	43,4	68,6
Median	46,1	66,9	44,1	53,9

The TSI values for Staw Płaszowski displayed minimal variability, as evidenced by a narrow interquartile range (IQR) and a median around 46, suggesting that this lake is mesotrophic. In contrast, Zalew Nowohucki had

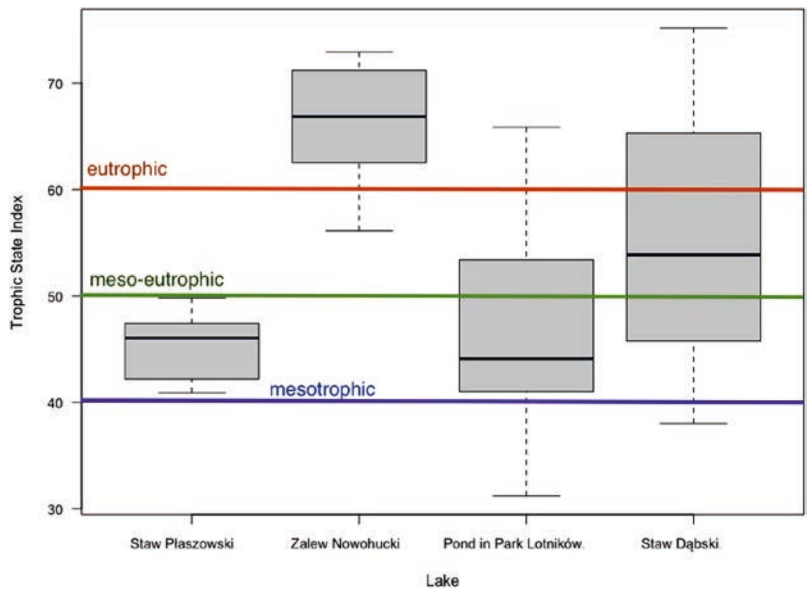

Fig. 9. TSI values in studied lakes with values for meso-eutrophic and mesotrophic lakes (based on Carlson, 1977)

a median TSI of approximately 67 with a slightly broader IQR, indicating moderate variability and classifying it eutrophic. The pond in Park Lotników had a median TSI of about 44 but exhibited a wide IQR and several outliers, reflecting high variability and categorizing it as mesotrophic. Staw Dąbski, with a median TSI of around 54 and a wide IQR, showed significant variability and elevated nutrient levels, marking it as meso-eutrophic (Fig. 9).

4. Discussion

4.1. Seasonal variability in *chlorophyll*-α content

The study demonstrates distinct seasonal variations in *chlorophyll*-α content across the four investigated water bodies. Staw Płaszowski exhibited consistently low and stable *chlorophyll*-α levels throughout the monitoring period, with no observed phytoplankton blooms. This stability indicates that Staw Płaszowski is relatively resistant to eutrophication, as the environmental conditions in this lake do not promote significant phytoplankton growth.

In contrast, Zalew Nowohucki exhibited significant fluctuations in *chlorophyll*-α content. Initially low in April, a sharp increase was observed by May 30, with high phytoplankton concentrations persisting for three weeks, indicating a bloom. This peak was followed by a drastic decline and another peak in June, suggesting a second phytoplankton bloom. This high variability and the presence of multiple peaks suggest dynamic environmental conditions and varying nutrient inputs. It is noteworthy that Zalew Nowohucki is the only lake connected to the Dłubnia River, which may contribute to its higher phytoplankton and cyanobacteria content.

Additionally, a gradual increase in average phytoplankton content from April to July was observed in Zalew Nowohucki (Fig. 7). Higher temperatures and increased sunlight availability are known to create favourable conditions for phytoplankton growth (Cheraghpour-Ahmadmahmoodi, 2024). Observations indicate that in some cases, *chlorophyll*-α concentrations corresponded to temperatures from one week prior, suggesting that temperature may have a delayed effect on phytoplankton development and, consequently, on *chlorophyll*-α concentrations. This leads to the hypothesis that prolonged high temperatures could have a cumulative effect on the occurrence of eutrophication. To investigate this, a further long-term study should be conducted, particularly during July and August, when daily temperature amplitudes are low, and temperatures consistently exceed 10°C.

The pond in Park Lotników exhibited moderate initial *chlorophyll*-α levels, with a gradual increase over time, reaching a peak by late April, indicating a phytoplankton bloom in early spring. Another peak at the end of May/beginning of June suggests a subsequent phytoplankton bloom. The rapid peaks in phytoplankton content, during which *chlorophyll*-α levels exceeded ten times the usual concentration, indicate that the pond is not resistant to eutrophication. This susceptibility can be attributed to the pond's early stage of biological development.

Both Staw Dąbski and Zalew Nowohucki experienced higher peaks in *chlorophyll*-α content, indicative of phytoplankton blooms likely due to nutrient pollution or other environmental factors. According to Rakocevic and Hollert (2005), ecosystems with greater diversity tend to shift from oligotrophic to eutrophic states. As previously described, the ecosystems of Staw Dąbski and Zalew Nowohucki are quite diverse, which may account for these seasonal peaks and elevated concentrations of phytoplankton.

The high variability in *chlorophyll*-α content suggests that estimating the trophic status of a lake based on a single sampling can be inaccurate. It is recommended to collect samples at least four times throughout different

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seasons but at the same time of day. Alternatively, samples should be taken four times during one day, to ensure a more accurate assessment.

4.2. Cyanobacteria content and its implications

The data on cyanobacteria content reveals significant differences in cyanobacterial proliferation across various water bodies. Zalew Nowohucki exhibited the highest variability and peaks in cyanobacteria content. There are many factors that contribute to cyanobacteria proliferation, with one of the most well-known being high nutrient content (especially phosphorus). Other contributing factors include low turbulence, adequate light, warm temperatures, and high dissolved organic matter (Paerl & Otten, 2013).

The pond in Park Lotników showed moderate fluctuations, generally staying below 2 μg/l but with noticeable spikes. Staw Płaszowski maintained relatively stable and low cyanobacteria content throughout the period, consistently showing the lowest levels among the four sites. This stability suggests environmental conditions less favourable for cyanobacteria, as the nutrient--driven growth of phytoplankton is the most common, and the overall lake system determines the process's outcome (Smith et al., 1987). Staw Dąbski displayed general stability with occasional spikes. These moderate fluctuations suggest some variability in nutrient inputs and environmental conditions, but not to the extent observed in Zalew Nowohucki.

The pond in Park Lotników exhibited the highest proportion of cyanobacteria in the total phytoplankton community, with a strong correlation between *chlorophyll*-α and cyanobacteria content. This high proportion could be attributed to the early stages of the pond's biological development. Cyanobacteria, known for their resilience and rapid growth, can quickly establish dominance in aquatic ecosystems. This dominance is often associated with high light absorption rates (Kosten et al., 2012). Prolonged cyanobacterial dominance can have detrimental effects, including reduced biodiversity (Reynolds, 1991). Therefore, the early establishment of cyanobacteria dominance in this pond is concerning and warrants further investigation.

Cyanobacteria blooms occur when the chlorophyll content reaches 10 μg/l (Kong, 2009), so during this study, no cyanobacteria blooms were detected. According to the WHO, for drinking water, a concentration of chlorophyll in the range of 1.0 μg/l is a threshold for Alert Level 1, which requires further consultation with health authorities to determine if the water is safe for consumption (Chorus & Welker, 2021). Alert Level 2 is defined as chlorophyll content >12 μg/l in drinking water and >24 μg/l in recreational water, necessitating immediate action (Chorus & Welker, 2021). No cyanobacteria content during this study reached the threshold of Alert Level 2, but it is advised that the water from the studied lakes should not be used for drinking purposes, or the cyanobacteria content should be monitored more regularly and in different locations within each lake to determine water safety for consumption.

4.3. Trophic state index and its variability

The Trophic State Index (TSI) provides a quantifiable measure of the nutrient status and trophic state of aquatic systems. According to Carlson (1977), TSI values greater than 60 categorize a water body as eutrophic, values between 50 and 60 as meso-eutrophic, and values between 40 and 50 as mesotrophic.

Staw Płaszowski demonstrated minimal variability in TSI values, with a narrow interquartile range (IQR) and a median of around 46. This suggests a stable trophic state with consistently low nutrient levels, placing the lake in the mesotrophic category.

It is well-established that TSI values can be influenced by the specific location from which samples are collected (Carlson, 1977). To accurately assess the trophic status of a lake, it is crucial to sample from multiple locations within the lake. Certain areas may exhibit less fluctuation in water quality, higher temperatures, reduced oxygen levels, and accelerated algal growth, which can impact TSI readings. Therefore, comprehensive sampling across diverse lake zones is essential for a reliable evaluation of its trophic state.

4.4. Correlations and implications for management

Statistical analysis revealed significant correlations between *chlorophyll*-α content and turbidity across the studied water bodies. The strongest correlation was observed in Staw Płaszowski (tau = 0.62), indicating that increases in phytoplankton biomass, as measured by *chlorophyll*-α content, are closely associated with increases in turbidity. This relationship suggests that elevated phytoplankton levels contribute to decreased water clarity and quality due to increased particulate matter.

Given the strong correlation between *chlorophyll*-α content and turbidity, it is imperative to employ meticulous sampling techniques to ensure accurate data collection. To avoid artificially increasing turbidity, samples should be collected with minimal disturbance to the substrate.

In the pond at Park Lotników, a substantial correlation between *chlorophyll*-α content and cyanobacteria levels (tau = 0.78) was observed. This indicates that in this pond, periods of elevated phytoplankton biomass are closely linked with higher concentrations of cyanobacteria, corroborating previous findings of a higher proportion of cyanobacteria within the total phytoplankton community.

A significant correlation (tau = 0.51) was also found between *chlorophyll*-α content in Zalew Nowohucki and the pond at Park Lotników, suggesting that these water bodies may share similar environmental conditions or nutrient inputs that affect phytoplankton growth. Notably, when air temperatures stabilized above 7°C, the correlation between Zalew Nowohucki and Staw Płaszowski increased to tau = 0.64. This stronger correlation underscores the influence of temperature on phytoplankton dynamics in these lakes, despite their distance of 7 km from each other.

5. Conclusions

This study reveals distinct seasonal variations in *chlorophyll*-α content across the four water bodies examined. Staw Płaszowski consistently maintained low and stable *chlorophyll*-α levels, indicating resistance to significant phytoplankton blooms and a stable state. This stability may be attributed to several factors. For instance, surrounding vegetation could provide shading, thereby reducing water temperature and limiting phytoplankton growth. Additionally, submerged macrophytes may contribute to nutrient uptake and thus reduce nutrient availability in the water column (Cao et al., 2025). More broadly, aquatic vegetation is widely recognized for its role in mitigating eutrophication processes (Li et al., 2026).

In contrast, Zalew Nowohucki experienced considerable fluctuations, with multiple peaks in *chlorophyll*-α content suggesting dynamic environmental conditions and nutrient inputs. The pond in Park Lotników and Staw Dąbski also showed significant variability, with rapid peaks indicating susceptibility to eutrophication, particularly in the pond's early developmental stage. These observations highlight the need for targeted management strategies for each water body's unique conditions.

Cyanobacteria content varied significantly among the water bodies. Zalew Nowohucki showed the highest variability and peak concentrations. The pond in Park Lotników had a high proportion of cyanobacteria, associated with its early development. While no cyanobacterial blooms reached critical alert levels,

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continuous monitoring is essential to manage potential health risks and water quality.

The Trophic State Index (TSI) indicated Staw Płaszowski as mesotrophic with low nutrient variability, Zalew Nowohucki as eutrophic with high nutrient levels, and the pond in Park Lotników as mesotrophic with high variability. Staw Dąbski showed seasonal fluctuations between mesotrophic and eutrophic states, underscoring the importance of regular and comprehensive sampling to capture these dynamics.

The observed correlations between *chlorophyll*-α content and turbidity in Staw Płaszowski indicate that increased phytoplankton biomass significantly impacts water clarity. Similarly, significant associations between *chlorophyll*-α levels across different lakes underscore the influence of environmental conditions on phytoplankton dynamics. The effect of temperature, particularly when it stabilizes above 7°C, further complicates these dynamics.

While analyzing chlorophyll and cyanobacteria content in these water bodies, it is important to consider that samples were collected from only a single location within each lake, which introduces limitations due to the heterogeneous distribution of phytoplankton. Future studies should include sampling from multiple locations within each lake to ensure that the selected points more accurately represent the overall condition of the water body.

It is challenging to pinpoint the exact factors contributing to variations in phytoplankton and cyanobacteria content, as numerous studies emphasize the necessity of considering the entire lake ecosystem (Smith et al., 1987; Kokociński, 2021). Phytoplankton dynamics are influenced by a complex interplay of multiple variables rather than a single factor. This study illustrates this complexity, as the lakes investigated are located within the same city and watercourse yet exhibit significant differences in phytoplankton and cyanobacteria concentrations.

Environmental factors influencing phytoplankton abundance include temperature, nutrient inputs (Salo & Salovius-Laurén, 2022), biodiversity, as well as lake surface area and depth. These variables interact in complex and interdependent ways, collectively shaping phytoplankton dynamics. Although eutrophication is a natural process, it has been markedly accelerated by anthropogenic pressures. Agricultural land use, for example, is a key driver of nutrient enrichment in aquatic systems (Withers et al., 2014), but it represents only one dimension of human impact. Climate change further modifies multiple environmental conditions, altering thermal regimes, stratification patterns, and oxygen availability (Nürnberg, 2025). It can also enhance the release of phosphorus from sediments under changing geochemical conditions (Holdt et al., 2025). In addition, direct human activities such as pollution discharge and water regulation increase nutrient loading – primarily nitrogen and phosphorus – thereby intensifying eutrophication (Devlin & Brodie, 2023).

Effective water management necessitates a comprehensive approach that integrates multiple environmental variables and their interactions (Manyuk et al., 2025). Future research should focus on long-term monitoring and extensive sampling to elucidate these relationships more clearly. Additionally, the study highlights the need for more rigorous monitoring of lake trophic states, especially in urban areas. Currently, Polish state monitoring primarily focuses on lakes in the northern regions of the country or those designated for recreational use, particularly where bathing takes place. Given the serious implications of eutrophication for coastal waters, it is imperative to consider the entire watershed, including urban lakes and other freshwater sources, in management and monitoring efforts.

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Author Contributions

Conceptualization: A.C., T.Ś.; Data curation: A.C.; Formal analysis A.C.; Funding acquisition T.Ś.; Investigation A.C.; Methodology A.C., T.Ś.; Project administration A.C.; Resources A.C.; Software A.C.; Supervision T.Ś.; Validation T.Ś.; Visualization A.C.; Writing – original draft A.C.; Writing – review and editing T.Ś

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Open Research Availability Statement

The *chlorophyll*-α, cyanobacteria content, and turbidity data, along with the R code used to generate the results in this study, are available on Zenodo. The dataset can be accessed via DOI 10.5281/zenodo.13889729 and the code via DOI 10.5281/zenodo.13964158. The code was developed using R Studio (version 2023.12.1+402). Additional materials, such as input data files or specific analysis scripts, are available upon request from the corresponding author.

To ensure the accessibility and discoverability of the samples used in this research, and to align with the National Science Foundation's guidelines of effective data practices, all samples used in this study have been registered with IGSN Global Sample Numbers through the System for Earth and Extraterrestrial Sample Registration ($SESAR^2$). $SESAR^2$ is maintained by the GeoInformatics Research Group of the Lamont-Doherty Earth Observatory. http://geosamples.org/ (accessed October 21, 2024).

Physical samples, registered at $SESAR^2$ and identified with IGSN persistent identifiers, are grouped by lake and can be accessed at the following URLs:

- Staw Płaszowski: https://app.geosamples.org/sample_group.php?group_id=429 (access: 24.04.2026).
- Zalew Nowohucki: https://app.geosamples.org/sample_group.php?group_id=430 (access: 24.04.2026).
- Pond in Park Lotników: https://app.geosamples.org/sample_group.php?group_id=431 (access: 24.04.2026).
- Staw Dąbski: https://app.geosamples.org/sample_group.php?group_id=432 (access: 24.04.2026).