

## Article

# Trophic Status of Lake Niesłysz (Poland) and Related Factors

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**Abstract:** In order to ensure the protection of lakes against eutrophication, an ongoing global problem, its causes should be determined on an individual basis. In this study, we investigated Lake Niesłysz in northwestern Poland in terms of (i) the impact of nitrogen and phosphorus on primary production, (ii) the Trophic State Index (TSI), and (iii) the hydromorphological characteristics and watershed features. We determined the thermal conditions, dissolved oxygen, organic matter, and selected forms of nitrogen and phosphorus. TSI was determined using Secchi depth (SD), chlorophyll *a*, total phosphorus (TP), and total nitrogen (TN). Hypolimnetic anoxia was observed in summer. Surface concentrations of chlorophyll *a* and organic carbon, total inorganic nitrogen (TIN), and total reactive phosphorus (TRP) were 5 µg L<sup>-1</sup>, 11.7 mg C L<sup>-1</sup>, 0.049 mg N L<sup>-1</sup>, and 0.018 mg P L<sup>-1</sup>, respectively. The TN:TP ratio was >30, while TIN:TRP was <10. The TSIs for chlorophyll *a*, SD, and TP ranged from 42 to 59, and for TN it was >145. The total trophic state index (T-TSI) exceeded 72. In conclusion, Lake Niesłysz has an average resistance to degradation and the catchment has little influence on the release and transport of biogenic matter into the lake. The limiting nutrient for primary production was phosphorus, but the influence of nitrogen or covariates of nitrogen cannot be excluded. Based on the oxygen conditions in the hypolimnion, the lake should be classified as eutrophic. Most of the TSIs were in the mesotrophic range, while the TSIs for TN and T-TSI classified the lake as hypertrophic. The results show that Lake Niesłysz is currently at a critical stage of progressive degradation, and it is advisable to develop and implement protective measures immediately.



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**Keywords:** nitrogen; phosphorus; Redfield ratio; lake resistance; susceptibility of catchment

## 1. Introduction

Lakes serve various ecological, social, and cultural functions, rendering them pivotal natural assets on Earth. However, they are relatively unstable and susceptible to degradation stemming from human activities [1,2]. A significant contributor to lake degradation is the influx of nutrients, particularly nitrogen (N) and phosphorus (P), which accelerate the inherently slow trophic growth cycle within lakes. This influx compromises water quality, disrupts lake productivity, and diminishes their socioeconomic utility [2–4].

To formulate and implement effective lake management strategies aimed at mitigating eutrophication and ameliorating environmental conditions in already affected lakes, we need to determine the lake's water quality and underlying processes [2]. An initial step involves assessing the trophic status, which serves as a barometer of lake water quality. While methods such as the determination of annual primary productivity and dissolved oxygen (DO) concentrations in the hypolimnion can be employed, their accuracy is not guaranteed [5]. Researchers may also use the Trophic State Index (TSI) devised by Carlson [6], which incorporates measurements of Secchi depth (SD), chlorophyll *a* concentration, and total phosphorus concentration (TP), or the method proposed by Kratzer and Brezonik [7], which includes the determination of total nitrogen (TN). One may also analyze morphometric lake characteristics and nutrient supplier influences as determinants of a lake's resilience

to environmental stressors. Exceeding a water body's tolerance thresholds can precipitate alterations in abiotic and biotic conditions and even total lake degradation [1,8].

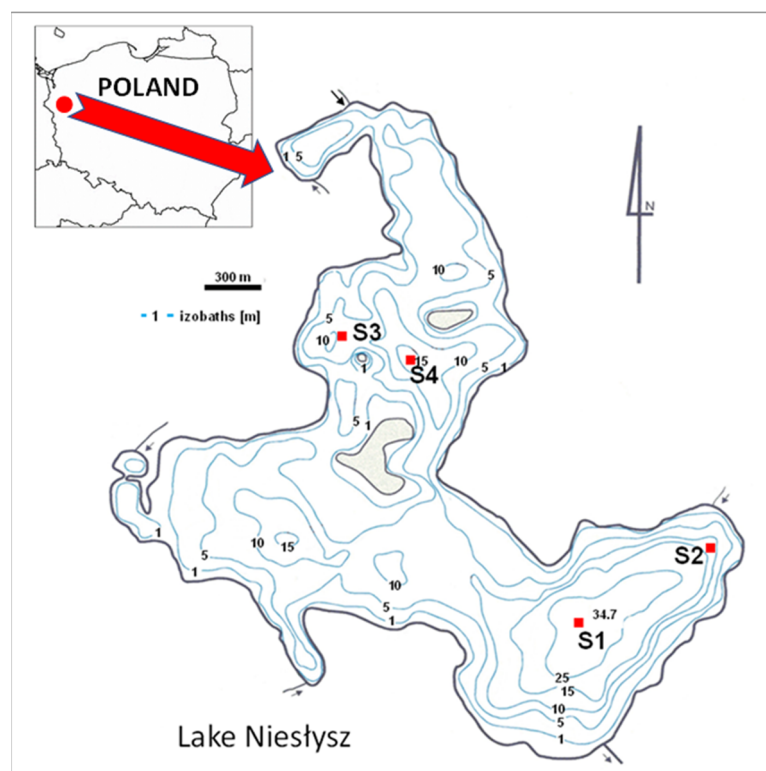
Information thus obtained aids in devising nutrient reduction goals and methods, although it needs to be stressed that effective eutrophication management necessitates individualized assessments for each lake due to the variable impacts of distinct factors on the relationships between hydromorphological variables, nutrients, chlorophyll *a*, and SD. Failure to account for these variations can lead to misconceptions regarding algal bloom intensities and inadequate protection measures for a given lake [3,4].

Considering the aforementioned factors, in this study we carried out a comprehensive evaluation of the trophic state of Lake Niesłysz, a water body with a significant tourism potential, and identified underlying factors. This entailed the determination of the lake's trophic state based on hypolimnetic oxygen conditions and trophic state indices (TSI) according to Carlson [6] and Kratzer and Brezonik [7], evaluation of the lake's range of tolerance to environmental pressures based on hydromorphological and catchment factors, and assessments of the limiting roles of nitrogen and phosphorus (Redfield ratio).

## 2. Materials and Methods

### 2.1. Study Area

Lake Niesłysz (52°14' N; 15°24' E) is located in the Torzyska Plain, part of the South Baltic Lake District (Figure 1). A distinctive feature of the area is its location within the area of the last glaciation, which has influenced the specific geomorphological, hydrographic, and soil conditions of the region and of Lake Niesłysz. It is a polygenetic lake—the northern part is located in a glacial trough, while the southern part was created due to moraine formation [9,10]. The morphometric data of the lake according to the bathymetric map of the Institute of Inland Fisheries (PR-1/9-182/60) are summarized in Table 1 [11]. The total and immediate catchment areas have a high proportion of forest, 47% and 85%, respectively [10].



**Figure 1.** Location of water sampling sites (S1, S2, S3, S4) from Lake Niesłysz (after [10]).

**Table 1.** Morphometric data and catchment data for Lake Niesłysz.

| Characteristic or Indicator | Unit                           | Value    |
|-----------------------------|--------------------------------|----------|
| Lake                        |                                |          |
| Surface area                | ha                             | 486.2    |
| Islands area                | ha                             | 10.4     |
| Maximum depth               | m                              | 34.7     |
| Mean depth                  | m                              | 7.1      |
| Volume                      | 10 <sup>3</sup> m <sup>3</sup> | 34,457.6 |
| Maximum length              | m                              | 4700     |
| Maximum width               | m                              | 1700     |
| Shoreline length            | m                              | 18,925   |
| Shoreline length of islands | m                              | 2050     |
| Catchment                   |                                |          |
| Total catchment area        | km <sup>2</sup>                | 56.24    |
| Arable land                 | %                              | 39.0     |
| Grassland                   | %                              | 3.5      |
| Woodland area               | %                              | 47.0     |
| Water                       | %                              | 9.5      |
| Built-up area               | %                              | 1.0      |

Lake Niesłysz is extensively fished by anglers. Small quantities of whitefish (*Coregonus lavaretus*), vendace (*Coregonus albula*), pike (*Esox lucius*), and tench (*Tinca tinca*) are caught, as well as larger quantities of the common bream (*Abramis brama*), roach (*Rutilus rutilus*), and white bream (*Blicca bjoerkna*). However, the main use of the lake is tourism and recreation. Resorts located around the lake attract around 120,000 tourists each summer [10].

## 2.2. Field and Laboratory Studies

Field surveys were conducted in winter (28 February 2023) and summer (21 August 2023). Water samples were taken using a Ruttner sampler (KC Denmark A/S, Silkeborg, Denmark) from a site located in the deepest region of the lake (site S1, 33 m deep) and from two sites (S2 and S3) located in offshore zones 8 m deep. During the summer, the oxygen and thermal profiles were also studied at site S4, 20 m deep (Figure 1). Badania terenowe wykonano zgodnie z procedurami opisanymi w APHA [12]. Water samples of 2.5 L were collected in clean polypropylene containers and cooled to  $4 \pm 1$  °C during transport to the laboratory. Samples for biochemical oxygen demand (BOD<sub>5</sub>) analysis were collected in glass bottles and incubated at  $20 \pm 1$  °C in the dark. Incubation was performed in a Memmert BE 500 natural convection incubator (MEMMERT GmbH+Co, Schwabach, Germany).

Water temperature and dissolved oxygen (DO) were measured directly in the field using a HI-98494 multi-parameter meter (Hanna Instruments, Woonsocket, RI, USA). Secchi depth (SD) was recorded using a 30-cm Secchi disc (KC Denmark A/S, Silkeborg, Denmark).

Hydrochemical indicators were determined according to the following methodologies recommended by APHA [12]:

- Standard Method 4500-NO<sub>2</sub><sup>-</sup> for nitrite nitrogen (NO<sub>2</sub><sup>-</sup>-N);
- Standard Method 4500-NO<sub>3</sub><sup>-</sup> for nitrate nitrogen (NO<sub>3</sub><sup>-</sup>-N);
- Standard Method 4500-NH<sub>4</sub><sup>+</sup> for ammonium nitrogen (NH<sub>4</sub><sup>+</sup>-N);
- Standard Method 4500-N for total nitrogen (TN);
- Standard Method 4500-P for total reactive phosphorus (TRP) and total phosphorus (TP);

- Standard Method 10200-H for chlorophyll *a* (CHL);
- Standard Method 5210-B for biochemical oxygen demand (BOD<sub>5</sub>);
- Standard Method 5310-B for total organic carbon (TOC).

Colorimetric methods employed a UV-VIS double beam spectrophotometer U-2900 (Hitachi High-Technologies Corporation, Tokyo, Japan). Total nitrogen (TN) and total organic carbon (TOC) were measured using a VarioTOC SELECT analyzer (ELEMENTAR, Langensfeld, Germany).

### 2.3. Assessing the Lake's Tolerance to Surrounding Environmental Pressures

The assessment of the natural resistance to degradation of Lake Niesłysz was carried out according to the methodology proposed by Bajkiewicz-Grabowska [8]. It takes into account 6 indicators (see Supplementary Materials, Table S1), which are assigned points from 0 (high resistance) to 3 (no resistance to catchment influence). The arithmetic mean of these scores allows the basin to be placed in the appropriate resistance category based on the data listed in Table S2.

The assessment takes into account the vulnerability of the lake catchment to the release and delivery of biogenic matter load to the lake, according to the system proposed by Bajkiewicz-Grabowska [8]. It takes into account 7 parameters, which are assigned a number of points on a scale from 0 to 3 (see Supplementary Materials, Table S3). The arithmetic mean of the awarded points for each parameter allows the catchment to be classified into one of four vulnerability groups (Table S4).

### 2.4. Determination of the Trophic State Index (TSI)

The calculation of TSI(SD), TSI(CHL), TSI(TN), and TSI(TP) are as follows [6,7]:

$$\text{TSI(SD)} = 60 - 14.41 \times \ln(\text{SD}) \quad (1)$$

$$\text{TSI(CHL)} = 9.81 \times \ln(\text{CHL}) + 30.6 \quad (2)$$

$$\text{TSI(TP)} = 14.42 \times \ln(\text{TP}) + 4.15 \quad (3)$$

$$\text{TSI(TN)} = 54.45 + 14.43 \ln(\text{TN}) \quad (4)$$

where SD is the Secchi depth (m), TP is the total phosphorus ( $\mu\text{g L}^{-1}$ ), CHL is the chlorophyll *a* ( $\mu\text{g L}^{-1}$ ), and TN is the total nitrogen ( $\mu\text{g L}^{-1}$ ).

The total trophic state index (T-TSI) value was mainly calculated using the following Formula (5), which is a standard that uses multiple parameters to summarize:

$$\text{T-TSI} = [\text{TSI(SD)} + \text{TSI(CHL)} + \text{TSI(TP)} + \text{TSI(TN)}]/4 \quad (5)$$

If the TSI value calculated is less than 40, it is called oligotrophic; if 40~50, mesotrophic; if 50~70, eutrophic; and if TSI is greater than 70, it is called hypereutrophic [6,7].

### 2.5. Statistical Analysis

Statistical analysis was performed using Statistica 13.3 software from TIBCO Software Inc. (Palo Alto, CA, USA). Pearson's linear correlation coefficient was used to analyze the relationships among the studied physicochemical indicators, with a confidence level of  $\alpha = 0.05$ .

## 3. Results and Discussion

### 3.1. Water Quality

The seasonal variability of water temperature in Lake Niesłysz, ranging from approximately 3.5–4 °C in winter to over 25 °C in summer (Table 2), is typical for lakes in temperate climates. These temperature ranges are observed in both shallow [13] and deep lakes [14,15].

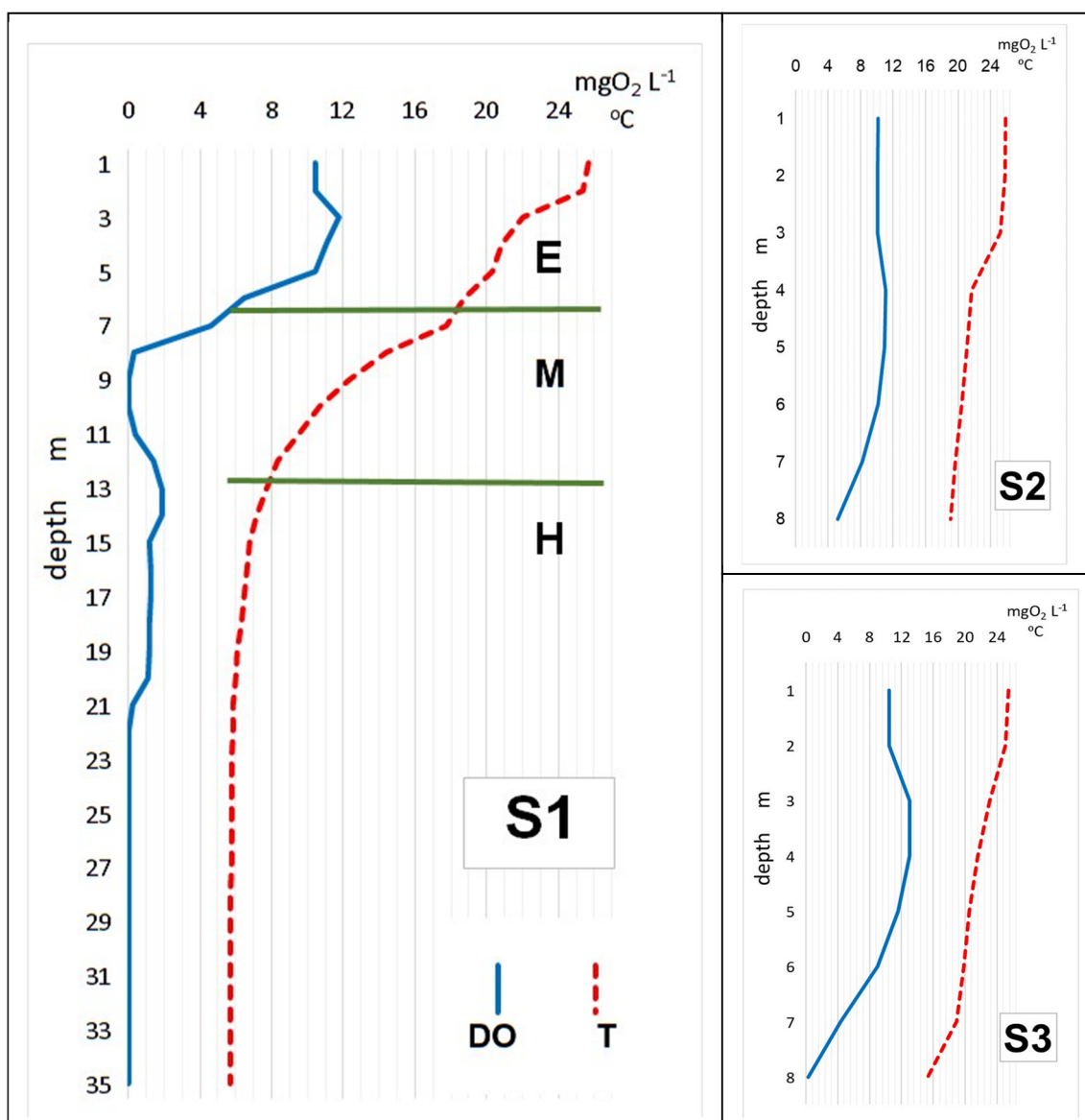
**Table 2.** Comparison of water temperature (T), dissolved oxygen (DO), biological oxygen demand (BOD<sub>5</sub>), total organic carbon (TOC), chlorophyll *a*, and Secchi depth (SD) in winter (W) and summer (S) at three study sites on Lake Niesłysz.

| Station | Depth<br>m | T<br>°C |      | DO<br>mg O <sub>2</sub> L <sup>-1</sup> |      | BOD <sub>5</sub><br>mg O <sub>2</sub> L <sup>-1</sup> |     | TOC<br>mg C L <sup>-1</sup> |      | Chlorophyll <i>a</i><br>µg L <sup>-1</sup> |      | SD<br>m |     |
|---------|------------|---------|------|-----------------------------------------|------|-------------------------------------------------------|-----|-----------------------------|------|--------------------------------------------|------|---------|-----|
|         |            | W       | S    | W                                       | S    | W                                                     | S   | W                           | S    | W                                          | S    | W       | S   |
|         |            |         |      |                                         |      |                                                       |     |                             |      |                                            |      |         |     |
| S1      | 1          | 4.0     | 25.7 | 14                                      | 10.2 | 4.6                                                   | 2.6 | 12.9                        | 11.7 | 1.9                                        | 5.3  | 7.5     | 6.5 |
|         | 4          | 3.5     | 20.9 | 13.6                                    | 10.7 | 3.4                                                   | 2.9 | 13.0                        | 17.1 | 2.3                                        | 5.3  |         |     |
|         | 8          | 3.8     | 14.4 | 13.5                                    | 6.6  | 4.0                                                   | 2.6 | 13.4                        | 12.1 | 1.9                                        | 4.7  |         |     |
|         | 14         | 3.9     | 7.2  | 13.2                                    | 3.6  | 3.5                                                   | 0.6 | 13.0                        | 19.8 | 2.3                                        | 2.1  |         |     |
|         | 20         | 3.9     | 6.0  | 13.3                                    | 3.4  | 4.9                                                   | 0.6 | 13.1                        | 12.1 | 1.9                                        | 2.1  |         |     |
|         | 33         | 4.0     | 5.7  | 13.2                                    | 1.0  | 3.5                                                   | 1.5 | 13.7                        | 19.9 | 1.9                                        | 2.1  |         |     |
| S2      | 1          | 4.0     | 25.8 | 14.1                                    | 10.1 | 4.7                                                   | 1.6 | 13.0                        | 11.6 | 1.8                                        | 10.7 | 7.0     | 6.0 |
|         | 4          | 4.0     | 21.7 | 14.1                                    | 11.1 | 3.7                                                   | 1.9 | 13.5                        | 17.0 | 1.8                                        | 16.0 |         |     |
|         | 8          | 4.0     | 19.1 | 13.4                                    | 3.2  | 4.2                                                   | 1.7 | 13.7                        | 12.2 | 1.8                                        | 5.3  |         |     |
| S3      | 1          | 4.0     | 25.5 | 14.4                                    | 10.5 | 5.1                                                   | 1.4 | 14.7                        | 16.8 | 2.3                                        | 17.5 | 7.0     | 5.0 |
|         | 4          | 4.0     | 21.6 | 14.1                                    | 13.1 | 4.6                                                   | 2.1 | 14.3                        | 12.0 | 2.4                                        | 17.1 |         |     |
|         | 8          | 4.0     | 15.3 | 14.3                                    | 1.6  | 4.6                                                   | 2.0 | 14.9                        | 18.5 | 2.4                                        | 23.5 |         |     |

In winter, homothermia (with the mean water temperature at about 4 °C) was recorded at all study sites (Table 2). In summer, permanent thermal stratification was recorded at site S1, with a warm epilimnion (7 m thickness, mean temperature 22.9 °C), a metalimnion formed under it (6 m thickness; mean temperature 13.1 °C, temperature gradient 1.7 °C m<sup>-1</sup>) and a hypolimnion (from 13 m depth, mean temperature 6.1 °C) (Figure 2).

The changes in thermal conditions were characteristic of deep temperate lakes. In summer, these lakes have thermal stratification, and in the winter season there is a reduction and equalization of temperature throughout the water mass due to full vertical mixing. Such lakes are classified as holomictic and, in the case of ice sheet formation in winter, dimictic [16,17]. In the case of Lake Niesłysz, in the winter season of 2021/2022, there was no formation of ice cover (as in previous years). In such a situation, water circulation takes a long time and lasts from autumn to spring, which according to [16] is characteristic of monomictic lakes. The shortening of the period of ice cover or even its complete absence and the lengthening of thermal stratification are observed in many temperate climate lakes. These phenomena result from climate change [14,15].

At sites S2 and S3 (with a depth of 8 m), homothermia was recorded in winter and two different situations of thermal conditions in summer. At site S2, the water column had epilimnion characteristics (average temperature 22.4 °C). In contrast, at site S3, a temperature of about 25 °C was observed in the surface layer (up to 2 m), followed by a thermal spike characteristic of the metalimnion (average temperature 19.5 °C, temperature gradient 1.63 °C m<sup>-1</sup>). Generally, such thermal conditions are observed in lakes with a polymictic mixing regime of water masses, in which, depending on the strength of the wind, full vertical mixing or partial mixing leading to the formation of a metalimnion is recorded [13,16,17].



**Figure 2.** Variability of temperature (T) and dissolved oxygen (DO) in the vertical profile at sites S1, S2, and S3 during the summer season (DO—dissolved oxygen in water, in  $\text{mg O}_2 \text{ L}^{-1}$ ; T—water temperature, in  $^{\circ}\text{C}$ ; E—epilimnion; M—metalimnion; H—hypolimnion).

In winter, DO concentrations were homogeneous throughout the vertical section, but slightly higher DO values were recorded at sites S2 and S3 than at S1 (average values of 13.8, 14.3, and 13.4  $\text{mg O}_2 \text{ L}^{-1}$ , respectively) (Table 2). In contrast, summer DO varied highly with depth at site S1, with maximum values in the layer up to 5 m depth (average 10.8  $\text{mg O}_2 \text{ L}^{-1}$ ), almost complete deoxygenation in the layer between 8 and 11 m depth (average 0.4  $\text{mg O}_2 \text{ L}^{-1}$ ), followed by a slight increase in DO between 12 and 20 m depth (average 1.4  $\text{mg O}_2 \text{ L}^{-1}$ ) and complete deoxygenation of the remaining hypolimnion waters (Figure 2).

Oxygen depletion is also common in the hypolimnion of stratified lakes, where oxygen exchange is cut off from the surface water and the atmosphere [18]. The determined oxygen profile of Lake Niesłysz at site S1 indicates the final stage of mesotrophy—a negative heterograde can still be distinguished [19], but the complete deoxygenation of the hypolimnion from 21 m depth indicates eutrophy. At this site in 2006, oxygen conditions characteristic of mesotrophy were recorded, DO in the entire hypolimnion was in the range of 2  $\text{mg O}_2 \text{ L}^{-1}$  to 3  $\text{mg O}_2 \text{ L}^{-1}$  [10]. At the same time, in successive deep-water zones of

the lake, those authors found anoxia from 9 to 10 m depth. We recorded the same result at the control surveyed site S4 (see Supplementary Materials, Figure S1), which indicates a progressive process of lake degradation, potentially leading to deoxygenation of waters in the metalimnion zone and the entire hypolimnion in the coming years. Analogous changes in trophic status were noted by Zdanowski et al. [20] or Pyka et al. [21] in the Mazurian Lakeland (Poland) lakes. This trend should be considered unfavorable for lake biocoenoses, especially ichthyofauna. Adequate oxygenation of the hypolimnion is essential for maintaining habitat and supporting fish reproductive cycles [18].

Deoxygenation of water in the over-bottom layer was also shown at site S3, opposite to site S2 (here the DO concentration in the over-bottom zone exceeded  $4 \text{ mg O}_2 \text{ L}^{-1}$ ) (Table 2, Figure 2). The differences may have been a result of the different influence of strong westerly winds (as reported by Konopczyński and Wąsicki [10]), dominant in this region, on the dynamics of water masses. Site S2, which lies in the western part of the lake, is exposed to a greater influence of westerly winds than site S3. This may have resulted in the circulation of the water masses of site S2 supplying oxygen to the zone near the bottom during the summer season. The water masses of site S3 were more stable, thus creating thermal stratification that favored the development of anaerobic conditions in the near-bottom zone in summer. Such phenomena are noted in shallow eutrophic lakes with a polymictic mixing regime [13,22].

The mean values of BOD<sub>5</sub> and TOC were  $4.2 \text{ mg O}_2 \text{ L}^{-1}$  and  $13.6 \text{ mg C L}^{-1}$  (winter) and  $1.8 \text{ mg O}_2 \text{ L}^{-1}$  and  $15.1 \text{ mg C L}^{-1}$  (summer), respectively. Mean concentrations of chlorophyll *a*, on the other hand, were  $2.1 \mu\text{g L}^{-1}$  (winter) and  $8.5 \mu\text{g L}^{-1}$  (summer) (Table 2). Concentrations of organic matter increased about 2 times from those recorded in 2006 by Konopczyński and Wąsicki [10], but they can still be considered low and characteristic of mesotrophic lakes of the Polish lowlands, such as in Lake Ińsko [23].

During the winter season, the average concentrations of nitrate nitrogen, ammonium nitrogen (in  $\text{mg N L}^{-1}$ ), and nitrite nitrogen and TRP (in  $\text{mg P L}^{-1}$ ) were 0.155, 0.021, 0.007, and 0.041, respectively (Table 3). In summer, site S1 showed a decrease in the concentration of nitrate nitrogen, ammonium nitrogen, and TRP in the surface layer (concentrations of about  $0.030 \text{ mg N L}^{-1}$ ,  $0.010 \text{ mg N L}^{-1}$ , and  $0.017 \text{ mg P L}^{-1}$ , respectively), an increase in the concentration of nitrate nitrogen at a depth of 14 m to  $0.226 \text{ mg N L}^{-1}$ , and an increase in the concentration of ammonium nitrogen and TRP in the over-bottom layer to  $0.480 \text{ mg N L}^{-1}$  and  $0.149 \text{ mg P L}^{-1}$ , respectively (Table 3). Such changes in the concentration of the inorganic forms of N and P are conditioned, on the one hand, by their intensive uptake by autotrophs in the trophogenic layer and release in the decomposition processes of the organic matter sedimenting into the deeper swarms of the basin. In the anaerobic zone, the reduced form of nitrogen and TRP are accumulated. It should also be borne in mind that anaerobic conditions promote the release of soluble forms of phosphorus from bottom sediments [21,24]. In the 2006 study [10], TP concentrations in the surface and bottom layers were similar to those shown in our study conducted in 2023, while ammonium nitrogen in the bottom layer was then about 10 times lower. These changes align with the observations of Ficker et al. [14], who demonstrated that expanding seasonal hypoxia and anoxia were correlated with prolonged seasonal stratification and increasing phosphorus concentrations in bottom-water layers. However, higher phosphorus levels in bottom waters did not increase the volume-weighted total phosphorus concentrations in the lakes.

Sites S2 and S3 did not show such high variation in the concentration of the inorganic forms of nitrogen and phosphorus in the vertical section during the summer season (Table 3). At the same time, higher concentrations of chlorophyll *a* and organic matter were recorded here than at site S1 (Table 2). These observations may indicate a positive effect of bottom sediments on primary production. This is consistent with the findings of Phillips et al. [25], who showed that shallow lakes have a higher yield of chlorophyll *a* per nutrient unit of P and N than deep lakes.

Comparing the obtained results with the threshold values regulated by the Regulation of the Minister of Infrastructure [26], it is challenging to classify the water of Lake Niesłysz

into a single purity class. In the winter season, TN concentrations at all sampling stations were within Class I purity (threshold value  $< 0.90 \text{ mg N L}^{-1}$ ). In the summer season, TN concentrations at stations S2 and S3 fell within Class II purity (not exceeding the threshold value of  $\leq 1.20 \text{ mg N L}^{-1}$ ). At station S1 during this season, water purity decreased with depth, and the bottom zone exceeded the threshold value for Class II purity (Table 3).

Total phosphorus concentrations in winter (throughout the entire vertical profile of all sampling stations) and in summer (in the bottom zone of stations S1 and S3) exceeded the allowable level for Class II purity (maximum  $0.05 \text{ mg P L}^{-1}$  according to the Regulation of the Minister of Infrastructure [26]). In the remaining water samples, TP concentrations met the Class II purity standard (Table 3).

**Table 3.** Nitrogen and phosphorus concentrations in the waters of Lake Nieslysz and the Redfield coefficient determined in winter (W) and summer (S), (TN—total nitrogen; TRP—total reactive phosphorus, TP—total phosphorus; TIN—total inorganic nitrogen as a sum of nitrite nitrogen, nitrate nitrogen, and ammonium nitrogen; av—average).

|         | Depth | NO <sub>2</sub> <sup>-</sup> -N |       | NO <sub>3</sub> <sup>-</sup> -N |       | NH <sub>4</sub> <sup>+</sup> -N |       | TN                   |       | TRP   |       | TP    |       | Redfield Ratio |      |         |      |
|---------|-------|---------------------------------|-------|---------------------------------|-------|---------------------------------|-------|----------------------|-------|-------|-------|-------|-------|----------------|------|---------|------|
| Station | m     | mg N L <sup>-1</sup>            |       |                                 |       |                                 |       | mg P L <sup>-1</sup> |       |       |       |       |       | TN:TP          |      | TIN:TRP |      |
|         |       | W                               | S     | W                               | S     | W                               | S     | W                    | S     | W     | S     | W     | S     | W              | S    | W       | S    |
| S1      | 1     | 0.007                           | 0.003 | 0.159                           | 0.038 | 0.015                           | 0.008 | 0.846                | 0.515 | 0.040 | 0.018 | 0.056 | 0.036 | 33.4           | 31.6 | 10.0    | 6.0  |
|         | 4     | 0.007                           | 0.002 | 0.152                           | 0.022 | 0.012                           | 0.011 | 0.856                | 0.529 | 0.037 | 0.016 | 0.055 | 0.036 | 34.4           | 32.5 | 10.2    | 4.8  |
|         | 8     | 0.007                           | 0.006 | 0.153                           | 0.016 | 0.016                           | 0.011 | 0.865                | 0.732 | 0.038 | 0.014 | 0.057 | 0.037 | 33.5           | 43.7 | 10.2    | 5.2  |
|         | 14    | 0.008                           | 0.006 | 0.151                           | 0.226 | 0.015                           | 0.002 | 0.829                | 0.827 | 0.035 | 0.015 | 0.053 | 0.030 | 34.6           | 60.9 | 11.0    | 34.5 |
|         | 20    | 0.006                           | 0.003 | 0.154                           | 0.122 | 0.018                           | 0.045 | 0.827                | 0.898 | 0.038 | 0.030 | 0.055 | 0.045 | 33.2           | 44.1 | 10.4    | 12.5 |
|         | 33    | 0.006                           | 0.006 | 0.150                           | 0.014 | 0.018                           | 0.480 | 0.869                | 1.633 | 0.047 | 0.149 | 0.069 | 0.162 | 27.8           | 22.3 | 8.2     | 7.4  |
|         | av    | 0.007                           | 0.004 | 0.153                           | 0.073 | 0.016                           | 0.093 | 0.849                | 0.856 | 0.039 | 0.040 | 0.058 | 0.058 | 32.8           | 39.2 | 10.0    | 11.7 |
| S2      | 1     | 0.006                           | 0.001 | 0.172                           | 0.035 | 0.016                           | 0.016 | 0.887                | 0.817 | 0.049 | 0.018 | 0.066 | 0.031 | 29.7           | 58.3 | 8.8     | 6.4  |
|         | 4     | 0.006                           | 0.004 | 0.170                           | 0.018 | 0.020                           | 0.009 | 0.885                | 0.811 | 0.057 | 0.016 | 0.071 | 0.037 | 27.6           | 48.5 | 7.6     | 4.3  |
|         | 8     | 0.007                           | 0.004 | 0.170                           | 0.017 | 0.027                           | 0.003 | 0.884                | 0.886 | 0.057 | 0.024 | 0.081 | 0.044 | 24.1           | 44.5 | 7.9     | 2.2  |
|         | av    | 0.006                           | 0.003 | 0.171                           | 0.023 | 0.021                           | 0.009 | 0.885                | 0.838 | 0.054 | 0.019 | 0.073 | 0.037 | 27.1           | 50.4 | 8.1     | 4.3  |
| S3      | 1     | 0.008                           | 0.002 | 0.154                           | 0.017 | 0.028                           | 0.005 | 0.883                | 0.936 | 0.037 | 0.014 | 0.053 | 0.037 | 36.8           | 55.9 | 11.4    | 3.8  |
|         | 4     | 0.008                           | 0.002 | 0.143                           | 0.017 | 0.029                           | 0.009 | 0.862                | 0.946 | 0.037 | 0.015 | 0.055 | 0.041 | 34.6           | 51.0 | 10.8    | 4.1  |
|         | 8     | 0.009                           | 0.001 | 0.137                           | 0.017 | 0.032                           | 0.011 | 0.843                | 0.975 | 0.042 | 0.045 | 0.066 | 0.066 | 28.2           | 32.7 | 9.4     | 1.4  |
|         | av    | 0.008                           | 0.002 | 0.145                           | 0.017 | 0.030                           | 0.008 | 0.863                | 0.952 | 0.039 | 0.025 | 0.058 | 0.048 | 33.2           | 46.5 | 10.5    | 3.1  |

Note: Classification of water according to the Regulation of the Minister of Infrastructure dated 25 June 2021 [26]—Class I, Class II, nc—no class.

The Pearson linear correlation analysis of the hydrochemical indicators is detailed in Table 4. Strong significant positive correlations were observed for the pairs T-CHL, DO-BOD<sub>5</sub>, NH<sub>4</sub><sup>+</sup>-N-TN, NH<sub>4</sub><sup>+</sup>-N-TRP, NH<sub>4</sub><sup>+</sup>-N-TP, TRP-TP, TN-TRP, and TRP-TP. Additionally, a strong negative correlation was found between T and NO<sub>2</sub><sup>−</sup>-N, T and NO<sub>3</sub><sup>−</sup>-N, and between CHL and NO<sub>2</sub><sup>−</sup>-N. These patterns are typical of lakes [27,28] and are driven by natural biochemical processes influenced by temperature. These processes include primary production (increased biomass and decreased nutrient concentrations due to uptake by autotrophs), the consumption of dissolved oxygen during the biodegradation of organic matter, and the concurrent release of phosphorus and reduced forms of nitrogen [19].

**Table 4.** Correlation analysis of temperature (T) and hydrochemical characteristics (DO—dissolved oxygen, BOD<sub>5</sub>—biochemical oxygen demand, TOC—total organic carbon, CHL—chlorophyll *a*, TN—total nitrogen, TRP—total reactive phosphorus, TP—total phosphorus).

|                                 | T     | DO    | BOD <sub>5</sub> | TOC   | CHL   | NO <sub>2</sub> <sup>−</sup> -N | NO <sub>3</sub> <sup>−</sup> -N | NH <sub>4</sub> <sup>+</sup> -N | TN   | TRP  | TP   |
|---------------------------------|-------|-------|------------------|-------|-------|---------------------------------|---------------------------------|---------------------------------|------|------|------|
| T                               | 1.00  |       |                  |       |       |                                 |                                 |                                 |      |      |      |
| DO                              | −0.28 | 1.00  |                  |       |       |                                 |                                 |                                 |      |      |      |
| BOD <sub>5</sub>                | −0.58 | 0.79  | 1.00             |       |       |                                 |                                 |                                 |      |      |      |
| TOC                             | 0.01  | −0.44 | −0.32            | 1.00  |       |                                 |                                 |                                 |      |      |      |
| CHL                             | 0.71  | −0.27 | −0.47            | 0.26  | 1.00  |                                 |                                 |                                 |      |      |      |
| NO <sub>2</sub> <sup>−</sup> -N | −0.83 | 0.45  | 0.68             | −0.07 | −0.74 | 1.00                            |                                 |                                 |      |      |      |
| NO <sub>3</sub> <sup>−</sup> -N | −0.82 | 0.46  | 0.54             | −0.11 | −0.68 | 0.71                            | 1.00                            |                                 |      |      |      |
| NH <sub>4</sub> <sup>+</sup> -N | −0.18 | −0.42 | −0.19            | 0.44  | −0.16 | 0.11                            | −0.22                           | 1.00                            |      |      |      |
| TN                              | −0.29 | −0.38 | −0.18            | 0.42  | 0.03  | 0.13                            | −0.09                           | 0.84                            | 1.00 |      |      |
| TRP                             | −0.49 | −0.20 | 0.13             | 0.35  | −0.30 | 0.33                            | 0.08                            | 0.89                            | 0.83 | 1.00 |      |
| TP                              | −0.47 | −0.18 | 0.14             | 0.36  | −0.26 | 0.33                            | 0.05                            | 0.87                            | 0.83 | 0.99 | 1.00 |

Notes: Red indicates significant strong or low positive correlations, while blue indicates significant strong or low negative correlations.

### 3.2. Redfield Ratio

The reported low concentration of chlorophyll *a* indicates the existence of factors limiting primary production. The most commonly analyzed are the effects of nitrogen and phosphorus, which can separately or together limit algal productivity [29]. It is recognized that as the total nitrogen (TN) to total phosphorous (TP) ratio (Redfield ratio) increases, the limiting effect of phosphorus increases [30]. In general, it has also been shown that TN:TP ratios decline significantly as lakes become more eutrophic [31]. The TN:TP ratio calculated in our study in winter at all sites and also in summer at site S1 was about 33. In contrast, in summer at sites S2 and S3, the TN:TP ratio exceeded 58 and 55 (Table 3), which indicates that phosphorus was a limiting nutrient in Lake Niesłysz.

The question of the limiting role of N and P looks different if one considers the forms of N and P directly taken up by autotrophs (that is, inorganic forms of nitrogen (TIN) and total reactive phosphorus (TRP)). In the trophogenic zone, TIN:TRP compared to TN:TP was more than 3 times lower in winter and from 5 (Site S1) to more than 10 (Sites S2 and S3) times lower in summer (Table 3). When TIN:TRP < 10, it is assumed that N is likely to be playing a limiting role [29]. Thus, it can be assumed that in Lake Niesłysz, nitrogen together with P may be a limiting factor for primary production. This confirms the results of Elser et al. [32], whose experimental meta-analysis showed equal limiting roles of N and P. In contrast, Liang et al. [33] showed that the limiting role of P is more likely under oligo-mesotrophic or eutrophic conditions, while the concurrent limiting activity of P and N occurs under hypertrophic conditions. The differences we have shown in the limiting roles of N and P, depending on the forms of these elements, indicate the need for more detailed studies. Understanding the limiting roles of N and P is important for the development and application of effective control of eutrophication, either by reducing both elements together or by reducing only one of them. Different methods and strategies are needed to control N and P and their costs vary widely [29,30].

### 3.3. Tolerance of the Lake to the Pressure of the Surrounding Environment

The final scores calculated for both analyzed groups of factors put Lake Niesłysz in Category II of resistance to degradation (mean 1.33) and its catchment in group 2 of susceptibility to the supply of matter to the lake (mean 1.29) (Table 5). Of the morphometric factors, the most unfavorable were the ratio of the water volume of Lake Niesłysz to the length of the shoreline and the percentage of water stratification (2 points in the classification for both). From the group of the so-called catchment indicators, the flow-through character of the lake and the 40% share of drainless areas in the lake's drainage basin should be considered particularly unfavorable (3 and 2 points in the classification,

respectively). They indicate a high risk of the lake to pollution from the lake's immediate surroundings, an increased possibility of inflow of pollutants from land and tributary waters, and a reduced capacity to retain nutrients in the hypolimnion [8,23].

**Table 5.** Assessment of the resistance of Lake Niesłysz to degradation and assessment of the sensitivity of the lake catchment to the release and transport of nutrient matter into the lake, based on Bajkiewicz-Grabowska [8].

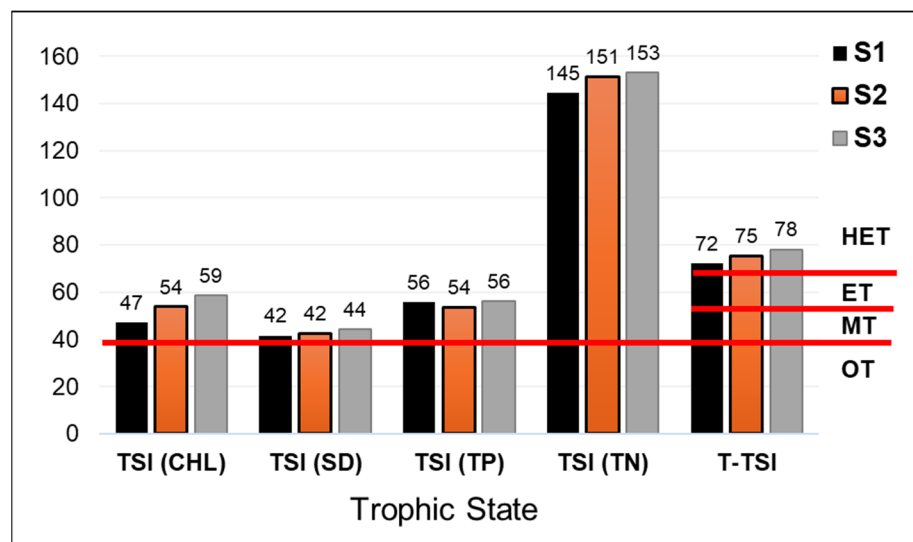
| Parameters                                                               |                                                                                            | Value               | Points                   |
|--------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|---------------------|--------------------------|
| The resilience of Niesłysz Lake to degradation                           |                                                                                            |                     |                          |
| Mean depth                                                               | m                                                                                          | 7.1                 | 1                        |
| Volume of the lake in relation to shoreline length                       | $10^3 \text{ m}^3 \text{ m}^{-1}$                                                          | 2.04                | 2                        |
| Percentage of lake stratification during summer stagnation               | %                                                                                          | 18.2                | 2                        |
| Surface area of the active bottom in relation to epilimnion volume       | $\text{m}^2 \text{ m}^{-3}$                                                                | 0.11                | 1                        |
| Intensity of water exchange                                              | %                                                                                          | 20                  | 1                        |
| Schindler's coefficient—quotient of total catchment to lake capacity     | $\text{m}^2 \text{ m}^{-3}$                                                                | 1.6                 | 1                        |
| Final Score (average)                                                    |                                                                                            |                     | 1.33                     |
| Category of lake resistance                                              |                                                                                            |                     | Category II              |
| Descriptive lake characteristics                                         | Medium resistance of a lake to the influence of its basin                                  |                     |                          |
| Susceptibility of the catchment area to supply material to Niesłysz Lake |                                                                                            |                     |                          |
| Ohle's Index                                                             |                                                                                            | 11.56               | 1                        |
| Balance type of lake                                                     |                                                                                            | Flow-through        | 3                        |
| Density of river network                                                 | $\text{km km}^{-2}$                                                                        | 0.8                 | 1                        |
| Average slope in catchment                                               | $\text{m km}^{-1}$                                                                         | 5                   | 0                        |
| Contribution of endorheic areas                                          | %                                                                                          | 40                  | 2                        |
| Geological structure of catchment                                        |                                                                                            | sand-loamy          | 1                        |
| Land use in catchment                                                    |                                                                                            | forest-agricultural | 1                        |
| Final Score (average)                                                    |                                                                                            |                     | 1.29                     |
| Groups of susceptibility of catchment                                    |                                                                                            |                     | 2nd susceptibility group |
| Descriptive catchment characteristics                                    | The basin has little influence on the release and transport of biogenic matter to the lake |                     |                          |

In general, Lake Niesłysz has an intermediate resistance to degradation, which is due to its relatively high average depth, a relatively favorable ratio of catchment area to lake volume, and 20% water exchange in the lake. Admittedly, the lake has a small active bottom surface relative to the volume of the epilimnion (a factor considered favorable), but as shown in Section 3.1, in summer the bottom waters of this zone can be deoxygenated and, as a result (see, e.g., [24,25]), raise the eutrophication of the waters by releasing nutrient elements, especially phosphorus, from the sediments.

The lake's catchment basin can be considered to have little influence on the release and transport of nutrient matter to Lake Niesłysz, due to the low values of the density of the river network, Ohle's Index, average slope in catchment, and its geological structure (mainly sand-loamy), as well as the significant share of forests in the catchment's land use structure (Table 5). The favorable parameters of these factors should moderately promote leaching from the catchment [8,23].

### 3.4. Level of Trophy

The calculated trophic status indices are shown in Figure 3. Values ranging from 42 to 59 were obtained for TSIs calculated from chlorophyll *a*, Secchi depth (SD), and TP. This range indicates mesotrophy [6]. The same trophic status was shown in 2006 (TSI(CHL) = 43; TSI(SD) = 44; TSI(TP) = 54) [10]. In contrast, TSI calculated from TN exceeded 145, which is characteristic of hypertrophy [7]. Hypertrophy is also indicated by the value of the total trophic state index T-TSI (range for the three sites from 72 to 78) (Figure 3).



**Figure 3.** Variability of trophic state indices (TSI) of study sites S1, S2, and S3 (TSI calculated according to the methodology given in Section 2.3; OT—oligotrophic; MT—mesotrophic; ET—eutrophic; HET—hypereutrophic).

The high discrepancy in the values of individual TSIs indicates that the growth of algal biomass in Lake Niesłysz is influenced by many different factors (it also depends on the depth of the body of water) and should be analyzed individually, as emphasized by [4,30,34]. For example, according to Carlson and Havens [35], the positive TSI (CHL)—TSI (SD) difference shown in our study indicates that the algal biomass in Lake Niesłysz was not limited by light availability, but also there should be more chlorophyll *a* than predicted by SD. In contrast, the small difference between TSI (CHL) and TSI (TP) suggests that N or some N covariate limited algal growth. At the same time, this is in contrast to the Redfield ratio for TN:TP, which indicates the limiting role of P. In light of the above discrepancies, nutrient bioassays should be conducted to confirm which factor limits the primary production of Lake Niesłysz.

## 4. Conclusions

Lake Niesłysz may be classified as a holomictic type with permanent stratification in summer and an oxygenated epilimnion and deoxygenated hypolimnion. Anoxia was caused by the mineralization of sedimenting organic matter, accompanied by the release of reduced forms of nitrogen and high concentrations of phosphorus and ammoniacal nitrogen in the bottom zone. The relatively low concentrations of chlorophyll *a* and organic matter in summer in the trophogenic zone indicate that primary production is limited by the availability of nutrient elements. The Redfield ratio indicates that autotroph biomass growth is limited by phosphorus. However, the limiting role of nitrogen cannot be ruled out.

Based on the anoxia of the hypolimnion, the lake can be classified as eutrophic. On the other hand, trophic state indices were in the range of mesotrophy (for TSI (CHL), TSI (SD) and TSI (TP)) or hypertrophy (for TSI (TN)). Characteristics of the catchment-lake system indicate that Lake Niesłysz is relatively resistant to the influence of the catchment, and the lake's catchment is not very active in providing nutrient matter. Nevertheless, an increase in

the eutrophication of the lake since 2006 has been demonstrated. This process, in addition to its negative effects on the biocenoses, may limit the possibilities for recreational use of the lake. Thus, it is necessary to identify in detail the factors degrading the lake (including nutrient bioassays) and develop a comprehensive strategy for the use and protection of the natural resources of the lake and its catchment area.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w16121736/s1>. Table S1. Grading criteria for lake resistance to basin influence after Bajkiewicz-Grabowska, 2010 [8]. Table S2. Categories of lake resistance to basin influence after Bajkiewicz-Grabowska, 2010 [8]. Table S3. Point criteria for the evaluation of a drainage basin as a supplier of matter to a lake after Bajkiewicz-Grabowska, 2010 [8]. Table S4. Groups of susceptibility of basins to the release and transport of biogenic matter after Bajkiewicz-Grabowska, 2010 [8]. Figure S1. Variability of water temperature (T) and dissolved oxygen (DO) in the vertical profile at site S4, during the summer season (DO—dissolved oxygen in water, in mg O<sub>2</sub> L<sup>−1</sup>; T—water temperature, in °C).

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