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Indicator Values of Emergent Vegetation in Overgrowing Lakes in Relation to Water and Sediment Chemistry

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Abstract: Lake overgrowth is one of the mechanisms affecting the gradual disappearance of lakes in the temperate zone caused by excessive eutrophication of waters. The aim of this study was to assess the possibility of using helophytes as bioindicators of lake overgrowth based on long-term changes based on the cartographic maps studies (1911–2012) and field analyses of plant form growth cover (2012–2014). Additionally, water and sediment chemistry in overgrowing lakes were investigated. The study comprised a total of 33 eutrophic lakes characterized by varying degrees of vegetation development. Based on discriminant analysis, four groups of lakes with diverse degrees of vegetation growth were distinguished. The group comprising the most overgrown water bodies was found to have the greatest percentage of helophytes, with a considerable proportion of submerged and floating-leaved macrophytes. Based on a review of archival materials, lakes which currently exhibit the highest degree of overgrowth were shown to have been affected by intensive littoral growth for over 100 years, which confirms bioindicator properties of helophytes in the assessment of the degree of lake overgrowth. In addition, lakes with the highest rate of overgrowth were characterized by a high content of nitrogen in sediment, with a concurrent high concentration of potassium.

Keywords: long-term studies; cartographic maps; lake disappearances; N and P limitation; macrophyte growth forms

1. Introduction

The disappearance of lakes in the temperate climate zone is associated mainly with their gradual shallowing and overgrowth caused mostly by excessive eutrophication of waters. Intense phytoplankton blooms contribute to the shallowing of lakes, which promotes increased availability of the lake area for settlement by macrophytes, especially emerged macrophytes. In lakes with high trophy, flow water transparency limits the development of submerged macrophytes [1–3], which in turn can only partially limit the development of emerged macrophytes (helophytes). This may be due to the lack of sufficient light necessary for the growth of plants at the beginning of the growing season. In turn, the high availability of nutrients favors the development of high productivity plants characterized by a fast growth rate [4–6]. This is reflected by large coverage of vegetation with low taxonomic differentiation. This is particularly visible by the intensifying succession of common reed, which has occurred in recent decades [7,8].

The rate of overgrowth of lakes varies depending on morphometric parameters of the lakes, size and depth primarily, and the availability of nutrients [9–11]. In shallow lakes, succession of macrophytes occurs faster, which is influenced by greater availability of areas of low depth, which is not a barrier to the succession of vegetation towards water depth. The intensive development of macrophytes may contribute to gradual shallowing of the lake due to deposition of organic matter from decomposing vegetation [9]. On the other hand, the large proportion of vegetation in the lake, especially the submerged one, contributes to the maintenance of good water quality by limiting the development of phytoplankton due to competition for nutrients, secretion of alloeopathic substances or limitation of sediment re-suspension [1,3,12]. The large development of macrophytes immersed in the water also indicates good ecological status of the lake, which is the basis for assessment of waters based on biological elements [13,14] according to the Water Framework Directive [15]. According to the theory of alternative stable states [16], conditions dominated by macrophytes (i.e., clean-water states) are preferred in lakes with high trophies, in contrast to the turbid state, dominated by phytoplankton. However, does the large proportion of macrophytes in the lake reflect a good status of the lake or is it a reflection of the intense process of its overgrowth?

On the other hand, assessment of the lake overgrowth process is only possible through many years of research [17–19]. Field tests of this type are conducted mostly in relation to selected water bodies [10,20]. Therefore, it is reasonable to use available archival cartographic materials to assess the scale of this phenomenon. However, archival maps include emerged vegetation, possibly with floating leaves. Modern remote sensing techniques allow assessment of the development of vegetation immersed in the last decades [7,21,22]. Therefore, assessment of the degree of overgrowing of lakes, or the amount of vegetation in lakes is possible only in relation to helophytes. In turn, there is a lack of recognition as to whether lakes with an intensive overgrowing process, observed over many years, are also characterized by a large share of submerged macrophytes, especially given the fact that coverage of submerged vegetation is reduced on a global scale [1,2,23].

Excessive human pressure intensifying the process of eutrophication of waters is the main factor affecting overgrowing of lakes [9–11]. This results in a high availability of nutrients in the lake. Taking into account the impact of submerged vegetation in the development of phytoplankton and accompanying biogeochemical processes, the quality of water in lakes with a high proportion of macrophytes is better than in eutrophic lakes dominated by phytoplankton. At the same time, these bodies should be characterized by a high level of nutrients in bottom sediments, stimulating the development of macrophytes and resulting from, among others, the deposition of phytoplankton. Therefore, it seems that the availability of nutrients in lakes with high trophies is not a factor limiting the development of macrophytes and, thus, is not a factor differentiating lakes with varying levels of overgrowth.

This research involved 33 lakes characterized by varied degrees of vegetation development. Changes in the range of emergent vegetation were analyzed in the period 1911–2014 on the basis of historical cartographic materials and current orthophotomaps and field studies. In all lakes, current studies on species composition of vegetation were performed, taking into account their various forms of growth and the chemistry of waters and bottom sediments. Three research hypotheses were assumed:

(1) A high proportion of emerged macrophytes in lake indicates the intensity of the lake overgrowth process without the need to take into account the participation of other forms of macrophytes, especially those submerged;
(2) Heavily overgrown lakes are characterized by intensive development of the helophyte zone observed in the multiyear scale;
(3) Eutrophic, strongly overgrown lakes are characterized by better water quality determined by higher levels of macrophytes compared lakes with low overgrowth rates, at the same time with high content of nutrients in bottom sediments.

2. Materials and Methods

This study was carried out in the Wielkopolska region, in the central-western part of Poland (Figure 1). The area is characterized by high agricultural production with high emphasis on water quality [24,25]. The study included 33 shallow (average depth < 9 m) lakes smaller than 130 ha and which characterized by different stages of overgrowth (Table S1). The lakes were created during the last Baltic glaciation. Catchment area of the studied lakes varied from 0.25 km^2 to 175.33 km^2 (with one exception 1560.29 km^2) (Table S1). The dominant land use in the catchments of 45% of lakes was arable fields (>53–79%), forest in 21% of lake catchment (>51–71%). The proportion of built-up areas varied from 0.3% to 33%.

Field studies were performed during vegetation seasons in 2012–2014. In order to recognize the stages of lake overgrowth, phytosociological investigations were carried out in the each of the lakes. Changes of emerged macrophytes range over time were analyzed based on cartographic maps from the beginning of the 20th century (1911–1913) to the beginning of 21st century (2009–2012). The trophic status of lakes was evaluated based on water and sediments parameters.

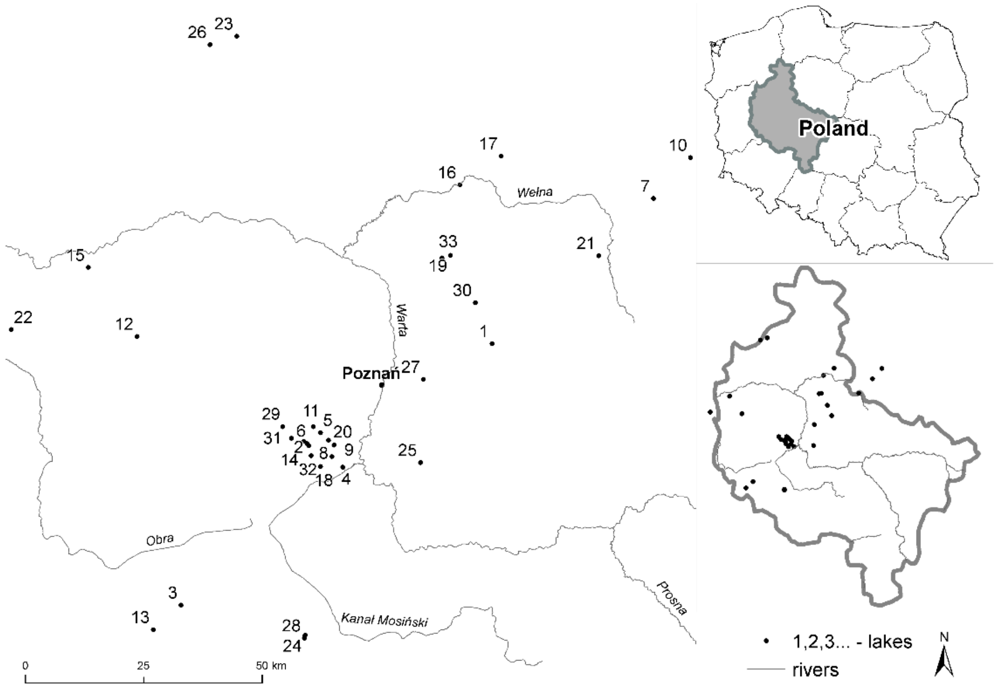

Figure 1. Localization of the lakes studied. Names of lakes are shown in Table S1.

2.1. Macrophytes

Composition of macrophyte species and coverage of dominant assemblages in each lake were determined during the vegetation season. Species composition was investigated using the Ciecierska method [6]. Plant coverage was estimated based on the Braun–Blanquet phytosociological approach with a seven-point scale [26]. Additionally, areas covered by the dominant macrophyte assemblages, include taxa of submerged, floating-leaved and emergent plant communities, assemblages were mapped with a Garmin GPSMAP 62s (Garmin International, Olathe, KS, USA). Syntaxonomic class affiliations were given according Matuszkiewicz [27].

2.2. Cartographic Analyses

Analysis of lake area changes and area covered by halophytes spanned the period from 1911–2012. Changes in lakes disappearance rates were calculated based on cartographic materials on the basis of lake surface changes (including lake waters and emerged littoral) in individual periods. Maps from the beginning of the 20th century were the starting point for analysis of changes in vegetation range in lakes. Surfaces covered by littoral in the 1980s and the second decade of the 21st century were calculated from the difference in open water surface area—not covered by vegetation—in relation to the lake surface designated at the beginning of the 20th century.

Analyses were based on German topographic maps called *Messtischblätter* in scale 1:25,000, which were one of the first available maps with triangulations, which is associated with correctness and very accurate mapping [28,29]. For the studied region, these maps were developed in 1888–1890, and updated in 1911–1913 (indicated in the paper as 1910). The range of the littoral zone of lakes, including helophytes and nympheides, on topographic maps was determined from the shoreline of the lake with their maximum occurrence determined on the basis of pictograms. The second source of cartographic materials included topographic maps in the "1965" coordinate system, which were made in the 1980s, at scale 1:10,000, in Cartesian quasi-stereographic secant projection (indicated in the paper as 1980). The range of vegetation was verified on the basis of aerial photographs. Current cartographic materials (valid for the period 2009–2012) included digital orthophotos and a spatial database (indicated in the paper as 2010), corresponding to the scale of the study 1:10,000 (Topographic maps TBD). The range of macrophytes was verified on the basis of direct GPS measurements made during field study (2012–2014). Analyses were carried out in the ArcGis program (version 10.3, ESRI, Redlands, CA, USA).

2.3. Water Samples

Water quality of the studied lakes was determine in open water during the summer. In situ measurements of electrical conductivity, water temperature and pH were carried out by potentiometers (Elmetron CP-401, CC-551, Elmentron, Zabrze, Poland). All samples, except for total N and P determinations, were filtered using Sartorius Cellulose filters (Sartorius GmbH, Goettingen, Germany) with nominal pore size of 0.45 μm. Collected water samples were cooled and analyzed in a laboratory at the Department of Ecology and Environmental Protection Poznan University of Life Sciences (Poznan, Poland), within a six-hour period. Concentrations of total phosphorus (acid persulfate digestion method), ortho-phosphorus (amino acid method), nitrite (ferrous sulphate method), nitrate (cadmium reduction method) and ammonium (Nessler's method) were determined using a spectrophotometer (HACH DR/2800, Loveland, CO, USA). Additionally, transparency (Secchi disc) and chlorophyll-a [30] concentration were determined.

Water quality was evaluated following Carlson's trophic state index (TSI) [31]. Carlson's index was calculated with mean values of total phosphorus concentration (TP), chlorophyll-a concentration (Chl a), and light visibility (Secchi depth; SD). Trophic states of each lakes were classified according to a TSI category: TSI < 40—oligotrophic (low productivity), TSI = 40–50—mesotrophic (moderate productivity), TSI = 50–70—eutrophic (high productivity) and TSI > 70—hypereutrophic (very high productivity).

2.4. Sediment

Sediment samples were collected from the surface layer (0–10 cm) using a 7-cm diameter Edelman corer (Geomor-Technik Sp. z o.o., Szczecin, Poland) from dominant plant species communities and in the pelagic zone. From each site, three random cores were collected and homogenized for further analyses. Each sample was divided into two parts. One part of the sample was directly frozen in dry ice for further determination of water quality. The second part was dried in the laboratory (70 °C, 48 h), ground and sieved through a 0.2 mm sieve. Dry samples were analyzed for total N, total P and K concentrations after digestion according to Kjeldahl's procedure. N and P were measured colorimetrically on a Specord 40 (Analytik Jena AG, Jena, Germany), and K concentration was measured by flame emission spectroscopy (BWB Model) (BWB Technologies, Newbury, UK).

2.5. Statistics

Heat map analysis with dendrograms based on hierarchical cluster analysis (HCA) was used to demonstrate similarities and differences between lakes in the studied groups of lake overgrowth with regard to macrophytes growth forms. Five-dimension variables were represented by colors.

Differences in the share of macrophytes in the studied periods (1910, 1980 and 2010), rate of lake overgrowth, percentage of lake disappearance and average water depth between selected groups of lake overgrowth were compared by analyses of variance (ANOVA) and a posteriori Tukey's test. Data were transformed using Box–Cox transformations to assess homogeneity of variance.

Dataset analysis was performed using the Spearman correlation analysis in order to evaluate the relationship between lake parameters of overgrowth changes and lake disappearance evaluated on cartographic materials and stage of lake overgrowth and macrophytes growth forms assessed by field studies. The purpose of these analyses was to test the possibility to use emerged vegetation as an indicator of lake overgrowth.

Principal component analysis (PCA) was used to analyze the physicochemical parameters of water quality and sediments of the studied lakes. Physicochemical water and sediments parameters were plotted in relation to the first two components generated by the factor analyses to illustrate the responses of individual lakes and groups to site physical variables. PCA made it possible to visualize the distribution of the lakes between the four groups on lake overgrowth.

Statistical analyses were performed using Statistica (version 13PL, StatSoft, Tulsa, OK, USA) software, except heat map analyses performed using the R computational platform (package 'd3heatmap').

3. Results

3.1. Degree of Lake Overgrowth

Analyses of the area covered by macrophytes in lakes identified four groups of lakes with varying degrees of vegetation shares (Figure 2), the highest having 71% bottom cover and the lowest with a plant share of only 6% in the lake (Figure 3). The proportion of littoral to the pelagial area decreased from 2.5 (Group 1), through 0.4 (Group 2), 0.2 (Group 3) to 0.06 (Group 4). Group 1 included lakes with the highest degree of overgrowth (N = 6), characterized by a 71% share of macrophytes in the lake. In this group, the share of emergent and submerged macrophytes was comparable and amounted to 32% and 31%, respectively. This group was also characterized by the highest coverage of nympheides, amounting to almost 8% of the lake surface. The second group (N = 7) included water bodies with an average vegetation share of 31%, with emergent vegetation (22%) having the largest share. The proportions of submerged macrophytes and nympheides were equal and amounted to 4%. The third and fourth groups of lakes had the lowest share of vegetation, covering only 16% and 6% of the surface of the lake, respectively. In Group 3 (N = 10), the proportion of submerged macrophytes was only 4%, with a small share of nympheides (1.6%). In Group 4 (N = 10), submerged vegetation was found in trace amounts (0.5%), similarly to plants with floating leaves (0.3%). On average, vegetation covered 6% of the lake's surface.

Average depth of the studied groups of lakes was the lowest (mean 1.45 m $\pm$ standard deviation 0.67) in the most overgrown lakes (Group 1). In the second and third groups of lakes average depth was comparable (3.04 $\pm$ 1.28, 3.49 $\pm$ 2.03, respectively). However, significant differences were detected only between the fourth group (average 6.12 $\pm$ 2.32) and the others ($F = 10.13$, $p = 0.0001$).

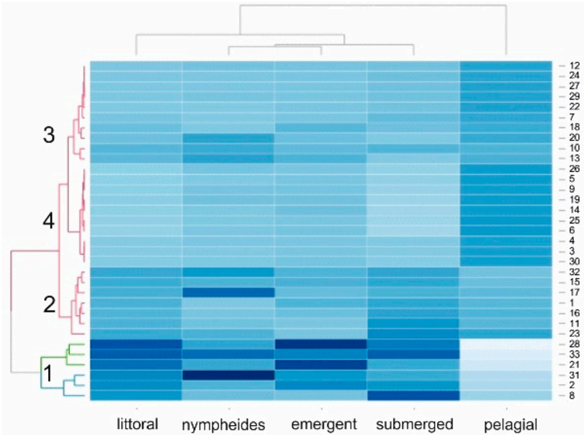

Figure 2. Correlation between studied lakes with regard to the macrophyte share (heat map) with presentation of a hierarchical tree plot to show the four groups of lakes characterized by a high similarity of species cover. The range of blue colors indicate the cover of macrophytes from light blue corresponding to the lack of macrophytes or their lowest cover to dark blue corresponding to their highest abundance. Names of lakes are shown in Table S1.

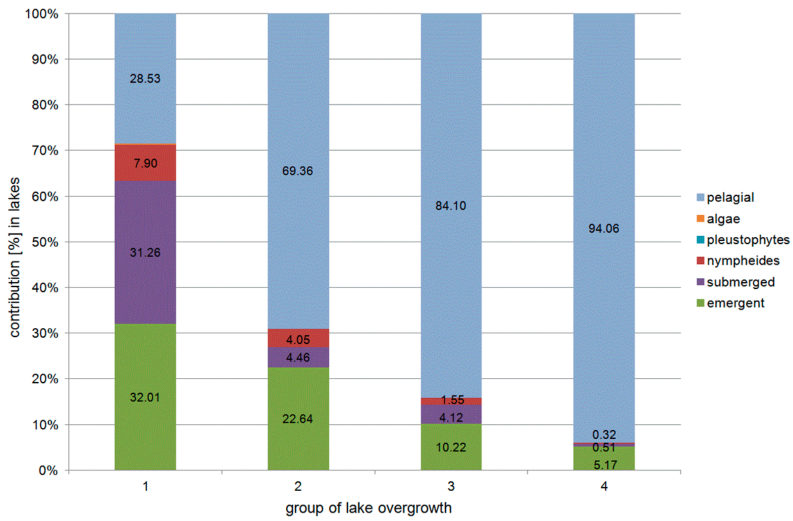

Figure 3. Contribution of growth of different forms of macrophytes and pelagic zone in the lakes between analyzed groups of overgrowing lakes (1—the highest, 4—the lowest).

3.2. Rate of Lake Disappearances and Overgrowth on the Basis of Maps

Analyses of cartographic maps based on evaluation of emergent vegetation showed a lack of differences in lake overgrowth between studied groups at the beginning at 20th century (Figure 4a). In 1980, significant differences were detected between analyzed groups (Figure 4b, Table 1). A decreasing trend was observed within analyzed groups. The highest rate of littoral zone development was observed in the first two groups, which showed the highest area covered by macrophytes (Figure 4c). The lowest area covered by emergent vegetation was detected in Group 4 where overgrowth of lakes over the century was the lowest.

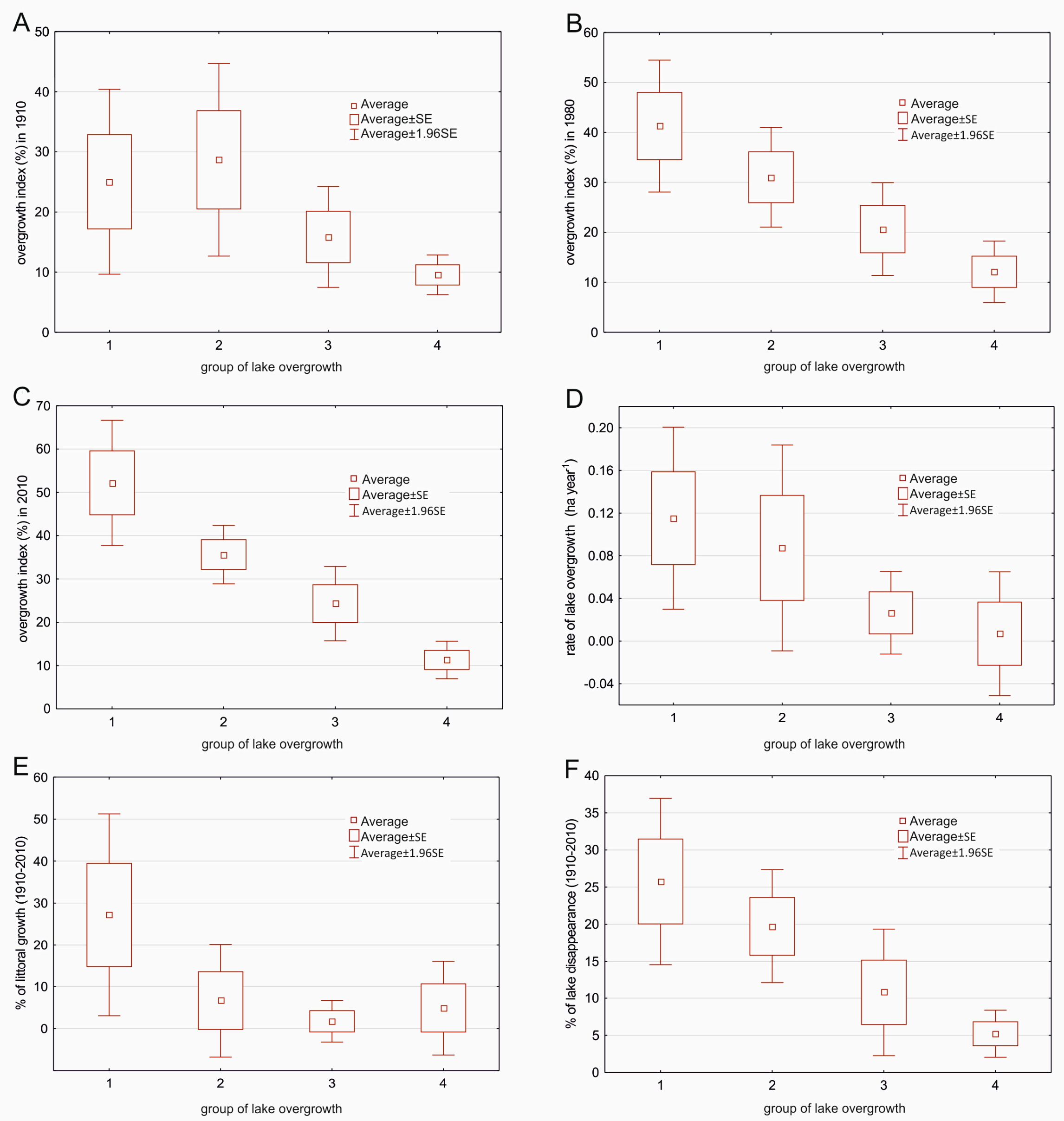

Figure 4. Share of emerged vegetation in lakes in (**A**) 1910, (**B**) 1980, (**C**) 2010 and (**D**) overgrowth rate, (**E**) percentage of littoral growth and (**F**) percentage of lake disappearance analyzed in the period 1910–2010.

The highest area covered by macrophytes was recognized in Group 1, characterized the highest rate of overgrowth. Differences between groups were biggest in 2010. The highest rate of lake overgrowth was detected in the Group 1 (Figure 4d); however, variability of data was biggest in this group. Also, the rate of lake overgrowth in the Group 1 (average = 0.11 ha·year^{-1}; Figure 4d) and percent of littoral zone development (Figure 4e) were the highest as a result of intensive growth of emergent vegetation. Significant differences were revealed between two groups characterized by the fastest and the slowest rates of overgrowth (Table 1).

Table 1. Results of one-way ANOVA testing the differences in share of emerged vegetation in lakes (i.e., overgrowth index) in 1910, 1980 and 2010, and overgrowth rate, percentage of littoral growth and percentage of lake disappearances between four lake overgrowth groups. All parameters were transformed using Box–Cox transformation. Data are F ratios and significance levels given as *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$ and ns, $p \geq 0.05$; df—degree of freedom.

Parameter	df	F	*p*
Overgrowth index in 1910 (%)	3	1.99	ns
Overgrowth index in 1980 (%)	3	7.04	**
Overgrowth index in 2010 (%)	3	13.82	***
Rate of lake overgrowth (1910–2010) (ha year^{-1})	3	4.33	*
Rate of lake overgrowth (1910–1980) (ha year^{-1})	3	2.25	ns
% of littoral growth (1910–2010)	3	2.53	ns
% of littoral growth (1980–2010)	3	2.89	ns
% of lake disappearance (1910–2011)	3	5.49	**

Comparison of lake areas between three periods showed the highest rate of disappearances for water bodies, characterized by the biggest area overgrown by emerged plants (Figure 4f, Table 1). In this group, lake areas decreased by an average of 25% over a century. Within the last group, some lakes showed a slow increase in lake area or did not change during the analyzed period.

To achieve the goal of evaluating lake overgrowth based on cartographic maps, we correlated the data with the results achieved during field studies, which included all macrophyte growth forms in all studied lakes (Table 2). All parameters obtained from maps significantly correlated with cover of emergent vegetation. The strongest positive relationships were observed between percentage of lake disappearance, the rate of lake overgrowth and the share of emergent plants compared to whole littoral zone (Table 2). However, these differences were not significant. The mean of the absolute value of Spearman's correlation coefficient among the nine underlying variables was r = 0.51. While the highest correlation (r = 0.77) was achieved between area cover by emergent vegetation estimated from maps (overgrowing index in 2010) in relation to the shoreline in 1910 and helophytes (emerged macrophytes) coverage measured in lakes by field measurements.

Table 2. Results of Spearman rank correlation between analyzed parameters of lake changes and different growth forms of macrophytes. Significance levels given as *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Parameter	Littoral	Nympheides	Emerged	Submerged	Pelagial
Overgrowth index in 2010 (%)	0.76 ***	0.50 **	0.77 ***	0.37 **	−0.73 ***
Overgrowth index in 1980 (%)	0.68 ***	0.39	0.73 ***	0.19	−0.63 ***
Overgrowth index in 1910 (%)	0.49	0.49	0.51	0.25	−0.39
Rate of lake overgrowth (1910–2010) (ha year^{-1})	0.34	0.14	0.39 *	0.08	−0.29
Rate of lake overgrowth (1910–1980) (ha year^{-1})	0.28	0.03	0.38 *	0.02	−0.23
% of littoral growth (1910–2010)	0.36 *	0.08	0.39 *	0.18	−0.33
% of littoral growth (1980–2010)	0.47 *	0.40*	0.38 *	0.52*	−0.52 *
% of lake disappearance (1910–2010)	0.50 **	0.27	0.58 ***	0.11	−0.45 **

3.3. Trophies of Lakes According to Physicochemical Parameters of Waters and Sediments

Analysis of physicochemical parameters of water and chlorophyll-a concentrations (Chl a) showed that the most differentiating factors of the bodies were the visibility of a Secchi disc (SD), chlorophyll-a concentration, aerobic parameters (biochemical oxygen demand (BOD5), oxygen saturation (%O_2)) and phosphorus (phosphate (PO4-P) and total phosphorus (TP)) concentration (Figure 5). The first group of factors explained 49% of variability, the second 28%. There were no significant differences between groups in relation to water trophies taking into account the parameters differentiating the tested lakes.

The trophic state of the lakes based on the Carlson's trophic state index (TSI) in individual groups of lake overgrowth showed a lower value in the group with the most overgrown waters, especially in relation to chlorophyll-a (TSI (Chl)) and visibility of the Secchi disc (TSI (SD)) (Table 3). The index of trophy, based on the concentration of chlorophyll-a, in strongly overgrowing lakes was lower than 50 in relation to the other groups of lakes indicating the intensification of water eutrophication (TSI (Chl) > 59). However, all groups of lakes were characterized by a very high content of total phosphorus in the water, corresponding to hypertrophy (TSI (TP) > 70). Differences between groups in relation to the total phosphorus concentration (TSI (TP)) were marginally statistically significant ($p = 0.08$).

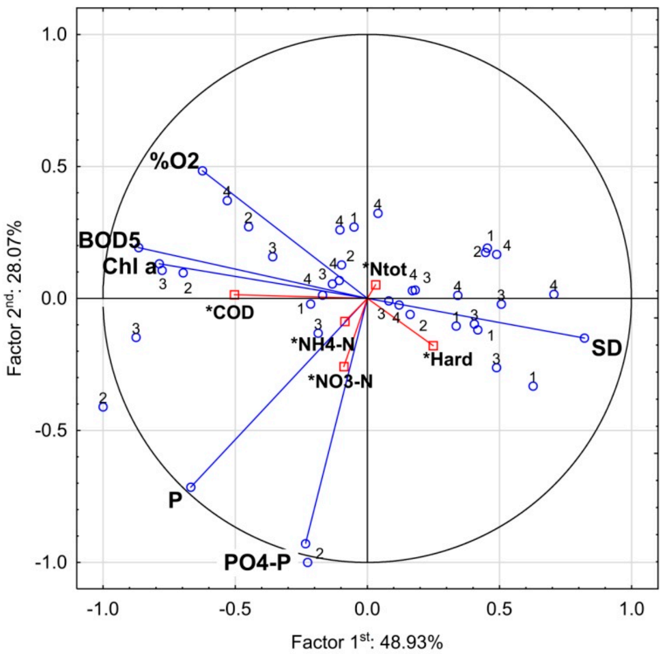

Figure 5. Principal component analysis for selected physicochemical water quality parameters (SD—Secchi disk visibility, BOD5—biochemical oxygen demand, %O_2—oxygen saturation, PO4-P—phosphate and TP—total phosphorus concentrations, COD—chemical oxygen demand, NH4-N—ammonium, NO3-N—nitrate, Ntot—total nitrogen, Hard—hardness) and chlorophyll-a concentrations (Chl a), of the studied lakes with regard to the groups of lake overgrowth (1—the highest, 4—the lowest).

Table 3. Values of Carlson's trophic state index (TSI) and its components (TSI based on chlorophyll-a concentrations—TSI (Chl), phosphorus concentrations—TSI (TP), Secchi disk visibility—TSI (SD)) (mean ± SD) for lakes in selected groups of overgrowth.

Group	TSI(Chl)	TSI(TP)	TSI(SD)	TSI
1	46.68 ± 8.45	73.79 ± 9.31	53.91 ± 10.92	58.13 ± 7.91
2	59.96 ± 14.81	81.55 ± 14.19	66.00 ± 8.53	69.17 ± 11.72
3	60.51 ± 15.15	80.02 ± 5.86	66.47 ± 15.94	69.00 ± 11.44
4	59.15 ± 14.27	71.25 ± 8.69	61.10 ± 10.12	63.84 ± 9.74

Differences between individual groups of lakes were important due to the chemistry of bottom sediments. PCA analysis explained 79% of total variability of lakes in the observed sediment parameters (Figure 6). The first principal component of sediment variables measured from all lakes explained 58.85% of variation in the data. PC1 describes the gradient of pH, nitrate (N), potassium (K) and conductivity (COD) in sediments. The second axis explained 20.09% of the total variation in the original data set. PC2 describes the gradient of phosphorus contents in sediments. The obtained results suggest that concentration of P was independent of N, K and conductivity. Simultaneously, pH predominantly influenced concentrations of N and K in individual lakes. Lakes with a high content of K, N and conductivity were mostly strongly overgrown reservoirs. The average nitrogen content was 10.7 mgN·100 g^{-1} sediments and potassium was 9.3 mgK·100 g^{-1} sediments (Table 4). Groups 2 and 4 showed high variance in respect to the analyzed parameters. However, the lakes with the lowest degree of overgrowth were characterized by the lowest concentrations of N and K, and the highest pH and P content compared to strongly overgrown lakes. N and K concentrations and conductivity decreased between groups as the share of vegetation in the lake diminished, contrary to pH of the sediments. In turn, the concentration of phosphorus was the highest in lakes with an average degree of vegetation share (Groups 2 and 3).

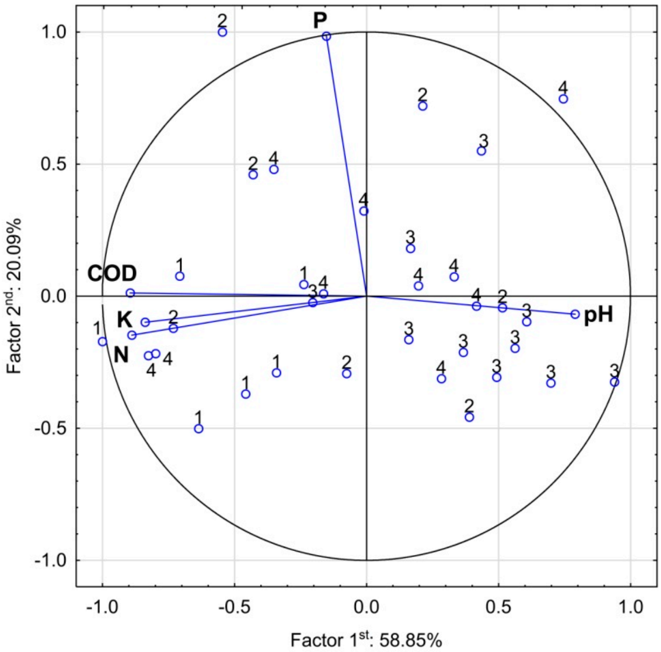

Figure 6. Principal component analysis for selected chemical sediment parameters of the studied lakes with regard to the groups of lake overgrowth.

Table 4. Variability in the selected chemical parameters of sediments in the analyzed group of lakes overgrowth (mean ± SD).

Group	pH	Conductivity	Nitrogen	Potassium	Phosphorus
		µS·cm^{-1}	mgN·100 g^{-1} sed.	mgK·100 g^{-1} sed.	mgP·100g^{-1} sed.
1	6.99 ± 0.09	1257 ± 221	10.67 ± 3.3	9.32 ± 4.29	1.65 ± 0.67
2	7.30 ± 0.41	831 ± 405	7.45 ± 2.65	6.92 ± 3.59	2.67 ± 1.66
3	7.33 ± 0.41	864 ± 425	6.41 ± 3.32	6.11 ± 4.23	2.33 ± 0.89
4	7.53 ± 0.46	545 ± 324	3.28 ± 2.45	3.41 ± 2.26	1.62 ± 0.84

4. Discussion

The presented results of eutrophic, high alkaline lakes, including the analysis of cartographic materials as well as field studies, allowed assessment of the pace of lake overgrowth and the conditions under which this process takes place.

4.1. Relationship between Macrophyte Forms in Overgrowing Lakes

Our study shows that lakes with the highest rate of overgrowth were characterized by the highest proportion of emerged macrophytes, at the same time having a large share of both submerged aquatic vegetation and with floating leaves (nympheides) (Figure 2). The proportion of helophytes was the highest in all lakes, and their cover decreased within groups of overgrowing lakes. These studies partly support observations by Kolada [4], who observed an increased share of emergent vegetation in littoral zone with increasing eutrophication. However, this study referred to changes in vegetation patterns in the total covered area, but not in relation to lake area. On the other hand, an increased share of helophytes, typically, is associated with a rise in water trophy in opposition to hydrophytes [8,32].

The shift from hydrophyte to helophyte dominance with increasing eutrophication was observed in a Polish lake with mean TSI values >55, with high P concentrations (>40.0 $\mu g \cdot L^{-1}$), TN > 1.0 $mg \cdot L^{-1}$, Chl a > 10 $\mu g \cdot L^{-1}$ and SD < 2.0 m [4]. In our study, all lakes were characterized by very high water trophy, and these changes could be observed within almost all of the studied lakes. Moreover, the highest proportion of emerged macrophytes in the lake (i.e., the percentage of macrophyte surface compared to lake surface) was accompanied by a large proportion of submerged macrophytes. It was also influenced by the availability for vegetation development of the lake. Our research also includes small lakes—below 50 ha—which were not included in waters monitoring by the European Union [14,15], characterized by the fastest overgrowth process.

The share of submerged macrophytes in lakes is beneficial to improvement of water quality by limiting re-suspension of sediments, competition with phytoplankton for nutrients, improvement of redox conditions or indirectly acting as an ecological niche for the development of zooplankton or fry [3,33,34]. Large proportions of submerged macrophytes in lakes contribute to reduction in the size of phytoplankton development, which can slow down the eutrophication process of the water basin. However, the share of submerged vegetation in lakes decreased with the decrease area of the littoral zone. Also, the rate of emergent vegetation in comparison to other groups of macrophytes in the littoral zone increased with decreasing areas covered by vegetation in lakes. Similarly, the proportions between particular forms of macrophytes changed from the most overgrown to those with the least overgrowth, to the disadvantage of not only submerged vegetation but also floating leaves. Many authors emphasize the intensification of the succession of common reed in European lakes resulting [7,8], among other things, from the high trophy of waters. Moreover, experimental studies suggest that growth in fertile habitats such as those emerging with *Phragmites australis*, *Typha angustifolia* or *Typha ssp.*, is not limited by the high concentration of nutrients [35–37].

On the other hand, a large proportion of nympheides in lakes is characteristic for waters with a high share of organic matter in bottom sediments and high nutrients and carbon availabilities [38,39]. Therefore, a large area of species like *Nuphar lutea* eutraphent [39] in the first group of lakes indicates higher fertility of sediments compared to other groups of lakes.

Our research also showed that the lakes with the highest degree of overgrowing showed a strong relationship with the most extensively declining ones. Therefore, a large share of littoral was typical for lakes characterized by high overgrowth and disappearance rate, which was associated with a significant share of rush vegetation at the same time. These results are explained partly by observations of Alahunhta et al. [40], indicating that helophytes are highly sensitive to changes in the catchment, or hydromorphological transformations. However, the dominant land use in the catchments of the most overgrown lakes differed was either arable land or forest, but strong human pressure on these areas has been observed in the last century [41]. On the contrary, submerged macrophyte communities can easily disappear with increased water turbidity (low transparency) due to light limitation [1,23]. Then, the interpretation of the state of lake disappearance based on hydrophytes can be doubtful. In addition, decomposition of submerged vegetation contributes to shallowing of lakes, which can stimulate the succession of emerged vegetation into open water in lake [42].

4.2. Cartographic Analyses in Lake Overgrowth

The analysis of cartographic materials showed that the group with the most overgrowing lakes was also characterized by the highest rate of lake disappearance and, at the same time, the highest overgrowth rate over the last century (Figure 4), most intensively over the last half century. These results indicate that a large proportion of vegetation in the lake, also emergent plants, may indicate the progressive process of overgrowing. Strongly overgrown waters were characterized by a share of macrophytes > 45%.

At the same time, these studies indicate that the analysis of overgrowth rate based on cartographic materials allows to assessment of the degree of overgrowth of lakes within the last 100 years, due to the significant share of macrophytes emerging in this process. Although the share of both submerged macrophytes and with floating leaves in overgrowth is a key element, development of the littoral zone, composed of rushes, takes place with greater intensity, and its share is dominant in the littoral zone of eutrophic lakes [43]. In our opinion, helophytes appeared to be a useful tool for bioassessment of lake overgrowth and disappearances. This approach makes it possible to evaluate the directionality of changes occurring in natural lakes of the temperate zone in which there are natural fluctuations of water levels. In lakes with significant water level variations, the development of vegetation will depend on their resistance to prolonged periods of drought or flooding [44].

Despite advanced techniques using satellite remote sensing techniques the long-term assessment of submerged macrophytes is still difficult, as well as being costly and time-consuming [7,21,22,45]. Luo et al. [46] emphasized that using only multispectral satellite image to identify and map submerged vegetation is difficult due to tiny spectral differences among species. In addition, these studies most often refer to lakes of considerable size, in contrast to small lakes where intense overgrowth processes observed. Many papers refer to the short period of research covering the last decades [45,47]. Limited recognition of the occurrence of submerged vegetation is also the result of high intensity of phytoplankton blooms, variability of water optical parameters, macrophyte coverage and differentiation or similarity of plant phenology [21,46]. In the case of the process of lake overgrowth, long-term analysis is necessary to indicate how much this trend is maintained and whether it is increasing. Assessment of dynamics of changes in the range of submerged vegetation over a long-term is not easy based on the indicated methods, due to the lack of sufficiently good source materials or being based on model studies. Therefore, a long-term analysis of the lake overgrowth process is possible in relation to the available historical topographic maps, taking into account emergent vegetation.

4.3. Trophy of Overgrowing Lakes

Research on water and sediment chemistry in all lakes showed high fertility, but varied between the analyzed groups of lakes. Although the PCA analysis of the physicochemical parameters of water and chlorophyll-a did not show a uniform division between the analyzed groups of lakes, the main gradient differentiating the studied water bodies—referring to the visibility of the Secchi disc and the intensity of phytoplankton blooms—a correlation with chlorophyll concentration in water was found. In general, lakes with the highest share of macrophytes were characterized by higher water transparency, associated with a lower concentration of chlorophyll-a. In this group of lakes, there were water bodies with a large proportion of submerged vegetation, which undoubtedly affected the quality of water. For example, Portielje and Van der Molen [48] observed an improvement in water quality in lakes with 5–10% of aquatic vegetation coverage. In some cases, even 50% was required to maintain a clear water state [49]. Lakes with lower transparency were distinguished from the group of lakes with a high degree of overgrowth by intensity of phytoplankton blooms. In contrast, Søndergaard and Moss [50] highlighted negative effects of submerged macrophytes on phytoplankton productivity and enhanced nutrient loadings within macrophyte beds [51,52]. However, detailed analysis of macrophytes showed that the impact on their condition resulted less from the presence of submerged macrophytes but, rather, from their congested form and species composition. Moreover, this aspect requires further deeper research relating to individual lakes and taxa. On the other hand, the analyzed lakes are located in the agricultural region, in which a high level of fertilization has been implemented for many years [25], and wastewater management has not been sufficiently regulated as yet [24]. High amount of nutrients coming from external sources causes high nutrient concentrations in water, which can be noted even under dense coverage of submerged macrophytes [53]. According to the theory of alternative stable stage [16] this stage of lakes is called hysteresis, which can easily switch into turbid stage with strong blooms of cyanobacteria, in the absence of submerge macrophytes—observed in the analyzed lakes.

Statistically significant differences in bottom sediment chemistry were found between groups of lakes with varying levels of overgrowth. The concentration of nutrients compounds, pH and conductivity were the most differentiating factors for the analyzed lakes. The highest content of nitrogen and potassium in water and the lowest pH of water were recorded in the lakes with the largest share of vegetation. Conversely, Søndergaard et al. [54] observed decreased macrophytes cover with enhanced of nitrogen when total phosphorus was in the range 0.1–0.4 mg·L^{-1}. Our results are consistent with Kolada [4] indicating that the intensification of emergent macrophyte development is observe with an increase in the availability of nitrogen in the lake. However, our research did not show such dependence in relation to the concentration of nitrogen in water but only in sediments. At the same time, the high nitrogen content was accompanied by high potassium levels. A study of Lawniczak et al. [55,56] showed that potassium stimulates nitrogen uptake by plants, which would confirm such dependence in strongly overgrowing lakes. However, nutrient concentrations in sediments are also modified by macrophytes which can partly explain differences between the overgrown lakes.

The lowest concentration of phosphorus was recorded in strongly and weakly overgrown lakes. This factor did not differentiate the lakes studied, although phosphorus is the most important factor limiting primary production in water bodies [54,57]. In strongly overgrown lakes, reduced phosphorus concentration may be partly due to uptake by plants. In the case of poorly overgrown lakes, it may be one of the factors limiting the development of vegetation. However, taking into account the concentration of phosphorus in sediments, its content was still high compared to other lakes of the temperate zone [57]. Moreover, factors limiting the development of macrophytes could also affect the availability of nutrients, for example soil characteristics, wind exposure, shoreline morphology [40] and first of all, water depth [8–60].

The weakly overgrown lakes were characterized by the highest average depth, higher than 2.5 m indicated as maximum depth suitable for submerged macrophytes growth and up to 3.5 m available also for the growth of nympheides [2,14]. Only within this group of lakes, water depth was one the most limiting factor for plant succession into lake. Moreover, in order to better understand the process of overgrowing of shallow lakes, it will be necessary to analyze long time water level changes in relation to vegetation dynamics. Therefore, water depth in shallow lakes can change significantly in subsequent years, for example as a result of climate change or intensification of water use [59,60].

Taking into account the climate changes currently occurring and the related increase in temperature, this may intensify the development of vegetation in lakes. This will be reflected in at change of plant species composition, including both species composition and forms of plant growth and their productivity. Considering the high rate of vegetation growth in lakes, this process may be accelerated, which in the case of eutrophic, shallow lakes may have dramatic effects, potentially leading to their disappearance [8,9]. Furthermore, shallow lakes are more vulnerable to overgrowth in conditions of trophy growth. Therefore, recognition of factors stimulating them is crucial for maintaining good quality waters while preserving their resources and slowing down the process of overgrowth.

5. Conclusions

Our study demonstrates that in lowland temperate lakes the process of lake overgrowth is linked with intensive growth of emergent vegetation. This group of macrophytes can serve as an indicator of lakes disappearances due to overgrowth because a large proportion of emergent macrophytes in a lake observed over a long-term scale can reflect the degree of advancement of lake overgrowing or at least can support the interpretation of the direction of their changes. In lakes with the currently highest degree of overgrowth, intensive development of the littoral zone was found over many years (1910–2010), which confirms the bioindicator properties of helophytes in assessing the extent of lake overgrowth. At the same time, lakes with the highest disappearance rates were characterized by the highest share of emerged vegetation.

Our research also showed the greatest diversity of forms of vegetation growth in strongly overgrown lakes, in which the share of hydrophytes and floating plants was also significant. This was reflected in better water quality, associated with greater transparency with limited phytoplankton development. However, these differences between the analyzed groups of lakes with different levels of overgrowth were not as significantly different as in the case of nitrogen and potassium in sediments. The results of the conducted research indicate that a high content of N and K is important for the development of vegetation, especially helophytes, in strongly overgrowing lakes. Therefore, the recognition of mechanisms of lake overgrowth, including the forms of plant growth, the degree of their development, the chemistry of waters and sediments and the degree advancement within lakes is crucial for proper assessment of water bodies, as well as planning protective activities and their management.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/10/4/498/s1. Table S1: Selected morphological parameters and localization of the lakes studied.

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