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Phosphorus inactivation mitigates the effect of warm winters in a temperate shallow lake (Mielenko Lake, Poland)

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Abstract Direct and indirect anthropopressure on water ecosystems is the serious problem throughout the world.. In the Northern Hemisphere, an increase in average air temperatures is observed, which implies the occurrence of a shorter period of snow and ice cover during the winter season. The winter 2019/2020 was unusual, because that was the first time in the record, that a complete lack of permanent ice cover was observed on numerous lakes in Poland. Such unusual conditions could influence lake functioning. Hence we analyzed the chemistry of the water–sediment interface (near-bottom and interstitial water and sediment) in the shallow, eutrophic Mielenko Lake (area 7.9 ha, max depth 1.9 m) in 2013 and 2019–2022 period to assess the influence of prolonged water circulation on the bottom zone. Mielenko Lake was subjected to a phosphorus inactivation procedure using Al and Fe salts (PAX 18, PIX 111) in 2020 and 2021. Our research revealed that unusually prolonged winter circulation caused a significant decrease in organic matter content in bottom sediment in 2020, as well as a decrease in NaOH-nrP fraction and TP amounts. That effect was short-term and it did not significantly influence the NaOH-rP fraction amounts. The released P was probably built in macrophytes biomass during vegetation season, because P inactivation has been limiting phytoplankton proliferation, and it favored shifting to a clearwater state with macrophytes domination. This was confirmed by decreasing in phytoplankton biomass, and a massive expansion of the macrophytes range noted in the second year of restoration. Our study shows, that P inactivation could mitigate the negative effects of warm winters in shallow lakes.

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Introduction

The water quality of some inland surface waters in Europe is still classified as poor or bad. Although the European Union introduced the Water Framework Directive more than 20 years ago, obliging the Member States to achieve at least good ecological status of water, the achievement of this goal is increasingly delayed. Member States allocate substantial funding to remedial actions (e.g. lake restoration), but with varying degrees of success (WFD, WWQA Ecosystems 2023; Carvalho et al. 2019).

Climate change is probably one of the most important challenges mankind faces today. The gradual increase in global temperature may generate many unfavorable phenomena, of which changes in the hydrological cycle as a result of increasing evaporation, increasing frequency of torrential rains and periods of severe droughts are the most important to lakes. This is confirmed by more and more studies and expert opinions (Otto 2020; Mann 2021; Popkiewicz et al. 2020). Human activity in the river or lake catchments, consisting of regulating rivers, urban development and hardening of the catchment surface, industrial activity (e.g. opencast mining) may further exacerbate the impacts of these phenomena, and ultimately hinder the processes of renewing groundwater resources and negatively affects surface water resources (Kundzewicz 2008, Scanlon et al. 2023). Concerns remain about the discharge of pollutants from point sources and diffuse sources where eutrophication is recognized as still the main pressure on surface water bodies (Bartram et al. 2002, EEA 2018).

The list of climate observations for Poland over the period 1991–2020, combined with the analysis of the period 1961–1990, clearly shows the negative effects of climate change in Poland. Increase in air temperature, more frequent occurrence of heatwaves, shorter periods with snow cover (Tomczyk and Bednorz 2022), as well as shortening the time of occurrence of the ice cover on Polish lakes (Marszelewski and Skowron 2006), that all can affect the functioning of lakes. In a simulation, Shatwell et al. (2019) showed that under climate change even the deeper, stratified lakes could change their mixing regime from dimictic to monomictic, because of a lack of ice cover. Such prolonged circulation, which extends the period of primary production may affect the functioning of water bodies.

Bottom sediment is an essential part of the lacustrine ecosystems. It can actively shape lake water quality due to the large nutrients pool deposited in the water–sediment interface zone, many times higher than phosphorus and nitrogen concentration in the other parts of the ecosystem (Augustyniak 2018; Søndergaard et al. 2003; Søndergaard 2007). The bottom area, contacting with circulating, warm water during summer is known as "the active bottom" (Augustyniak 2018). Phosphorus and nitrogen internal loading processes are very intensive in "the active bottom" area. That zone is relatively small compared to the whole lake bottom area and lake water volume in the deep, stratified lakes. However, the entire bottom area is "active bottom" in shallow lakes, and the internal loading processes are much more intensive there. This is the main reason for the shallow lakes' susceptibility to degradation (Abell et al. 2020; Søndergaard et al. 2003; Søndergaard 2007). Shallow lakes are more productive and more susceptible to excessive external nutrient loading, because of limited water volume for the dilution of pollutants. In the case, that such lakes have been polluted in the past, internal loading can be a serious source of nutrients that remain available for lake primary production even when external load has been controlled (Abell et al. 2020; Grochowska et al. 2021). Consequently, properly restoring of those nutrient-impacted lakes involves tackling this internal load to which chemical P inactivation is one of the most effective methods currently available. (Abell et al. 2020; Lürling et al. 2016; van Oosterhout 2022). These interventions usually do not consider changed climate conditions, which may affect P inactivation. For example, a heat wave reduced the efficacy of P inactivation in the laboratory (Zhan et al. 2021), and in an enclosure experiment (Zhan et al. 2022), likely through accelerated biogeochemical processes keeping more P locked in the biological loop (Zhan et al. 2022). However, those studies focused on summer extreme climate events, while the impacts of climate-related changes in winter are less well studied.

Theoretically, shallow polymictic lakes could be prone to a lack of ice cover and shift to the whole year circulation and production cycle. This means, that in such a situation together with rising water temperature, organic matter mineralization, and primary production probably could be more intense. This could influence the water quality in the lake. Hence the aim of this study was to get more insight in the possible effects of P inactivation on the mitigation of negative changes induced by lack of ice cover. To this end, we performed.

- analysis of the influence of restoration on nutrients concentration in the water–sediment interface of northern, temperate shallow Mielenko Lake (Poland),
- analysis of the direction of changes in nutrient amounts in the water–sediment interface of Mielenko Lake, induced by the lack of permanent ice cover during the winter season.

Methods

The object of study

The research was conducted on Mielenko Lake, located in Kartuzy City (Kashubian Lakeland, Northern Poland). The analyzed water body is small (area 7.9 ha) and shallow (max. depth 1.9 m). It is the highest-located lake in the Kartuzy Lakes complex. The outflow (Klasztorna Struga River) directs water into Karczemne Lake. Basic morphometric data of Mielenko Lake are shown in Table 1.

Depth index (DI) value (0.684) confirms the hemispherical shape of the lake bowl. Because of the low maximum depth and lake bowl shape, the whole bottom area in Mielenko Lake can be characterized as "an active bottom", which is subjected to high temperatures during the summer season. Shallow lakes have polymictic water circulation, resulting in a dynamic circulation of matter. Before restoration, Mielenko Lake was a typical eutrophic water body, with low water transparency due to phytoplankton blooms (Grochowska et al. 2019, 2022). The phytoplankton biomass value was characteristic of a moderate ecological state, according to criteria by Hutorowicz and Pasztaleniec (2011).

The bottom sediment of Mielenko Lake was effective in P adsorption in oxic conditions, showing a very low P equilibrium concentration and rather high maximum sorption capacity (Augustyniak and Serafin 2021).

Sampling

The bottom sediment samples (3 undisturbed sediment cores during every sampling) were taken

Table 1 Morphometric characteristic and basic catchment data of Mielenko Lake (Grochowska et al. 2019)

Parameter	Units	Mielenko lake
Area	ha	7.8
Maximum depth	m	1.9
Average depth	m	1.3
Maximum lengtht	m	460
Maximum width	m	252
Relative depth index (Halbfass formula)	–	0.0068
Volume	Thousand of m^3	102.9
Depth index	–	0.68
Shoreline development index	–	1.3
Shoreline length	m	1,314
Total catchment area	ha	382
Direct catchment area:	ha	22.1
Forests	%	65
Meadows	%	34
Urban area	%	1

using a Kajak sediment sampler (model 13,030, KC-Denmark, Denmark) at one research station, located in the deepest, central part of the lake. Near-bottom water (10 cm thick water layer directly above sediment) was decanted. The sediment core was pushed towards the top of the apparatus using a piston. Then sediment was divided into 5-cm thick (0–5 cm and 5–10 cm) layers and every layer was placed directly into the container. During every sampling three cores were taken and divided into two, 5-cm thick layers. Such sediment division was caused by the fact, that the top sediment layer was highly hydrated and semi-liquid (H_2O content exceeded 93–95%), and this made the division into thinner layers difficult with technical point of view. Interstitial water was separated from sediment via centrifugation (3000 rpm, 20 min). Water analysis included: nitrogen forms (N-NH_4, organic N, TKN), phosphorus forms (P-PO_4, organic P, TP), iron (spectrophotometrically on Merck Spectroquant Prove 100 or Nanocolor, Macherey–Nagel; TN was measured on IL-550 TOC-TN Analyzer by Hach Inc.). Sediment analysis was made according to methods described in Augustyniak et al. (2019) and included: organic matter, silica, nitrogen, iron, aluminum, and calcium determination. Sediment phosphorus fractions analysis was performed according to the method described by van Hullebusch et al. (2003) and included: labile P (NH_4Cl-P), phosphorus sensitive to redox potential changes (BD-P), phosphorus bound to aluminum and iron hydroxides (NaOH-rP), phosphorus bound to organic matter (NaOH-nrP), phosphorus bound to calcium compounds (HCl-P) and non-reactive residual phosphorus (res-P).

Water transparency was measured using a Secchi disc.Samples for phytoplankton biomass were taken from the surface, 1 m and 1.9 m depth meter using a Ruttner water sampler (3 L) and poured into the bucket. After thorough mixing, a final sample (200 mL volume) was taken from the bucket and preserved immediately using buffered Lugol's solution. Later, sub-samples were analyzed for phytoplankton biomass according to methods: CEN EN 2006, DIN CEN 2015, Napiórkowska-Krzebietke and Kobos (2016).

All obtained results were subjected to log (n + 1) transformation (an approximation to normal distribution) and statistically analyzed using Statistica 14.5 software package (Tibco Inc.). One-way and three-way ANOVA analysis (with Tukey HSD posthoc test) was performed to find the significant differences in the annual averages of chemical parameters. The tested factors were: water layers (three levels—near-bottom water, interstitial water 0–5 cm and 5–10 cm) or sediment layers (two levels—0–5 cm and 5–10 cm), restoration: (three levels – before, during and after), and year (five levels – years).

The principal components analysis (PCA) was performed Statistica 14.5 software package (Tibco Inc.) PCA analysis was used to find potential correlations between water and sediment chemical parameters and the winter season and vegetation season mean temperatures in research years (Fig. 1).

The amounts of nutrients in sediment (on the area below 1.5 m depth) were assessed using data on the concentration of particular components (total phosphorus, phosphorus fractions, total nitrogen) and sediment hydration, which was measured gravimetrically.

Phosphorus inactivation procedures implemented on Mielenko Lake

In 2020 and 2021 Mielenko Lake was restored by phosphorus inactivation method. Two preparations – PAX 18 (polyaluminum chloride) and PIX 111 (ferric chloride) (Kemira Inc.). Two applications (early spring and late autumn) were performed every year giving four dosing in total. During each dosing PIX 111 (2,260 kg) was applied on shallower parts of the lake, whilst PAX 18 (2,485 kg) was dosed in the deepest area of the lake. Biomanipulation was also applied on Mielenko Lake as a supporting measure. Predatory fish (pike *Esox lucius* L.) were introduced to the lake (three introductions, 10,000 summer fry individuals per one introduction). The removal of undesirable species of *Cyprinidae* was applied as well (three removals – 40 kg of fishes in total with some cyprinids fry. Removed fishes were introduced to other water bodies). The removal was not such effective as it was expected because of high EC of water. (Grochowska et al. 2019).

Weather conditions during the research period

Mielenko Lake is located in the temperate climate zone. The average amount of precipitation for this

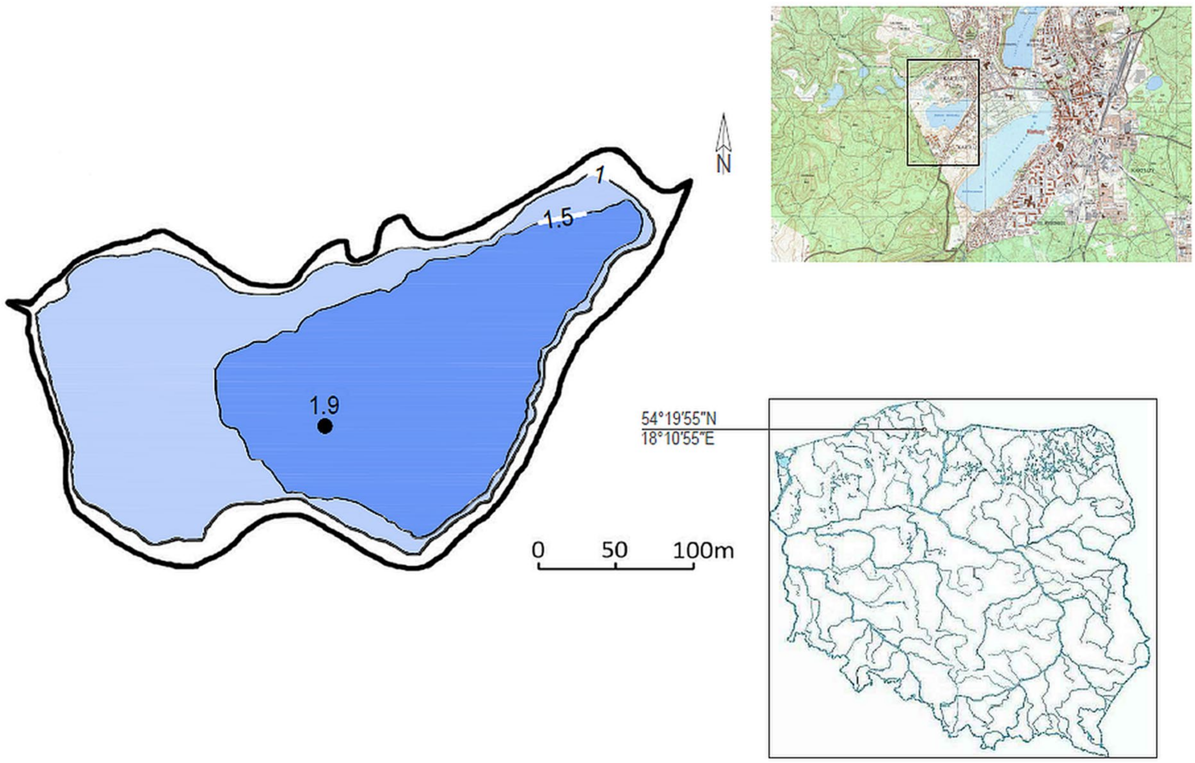


Fig. 1 Bathymetric map of Mielenko Lake with location of sampling point (sources: Grochowska et al. 2019, www.geoportal.gov.pl, changed)

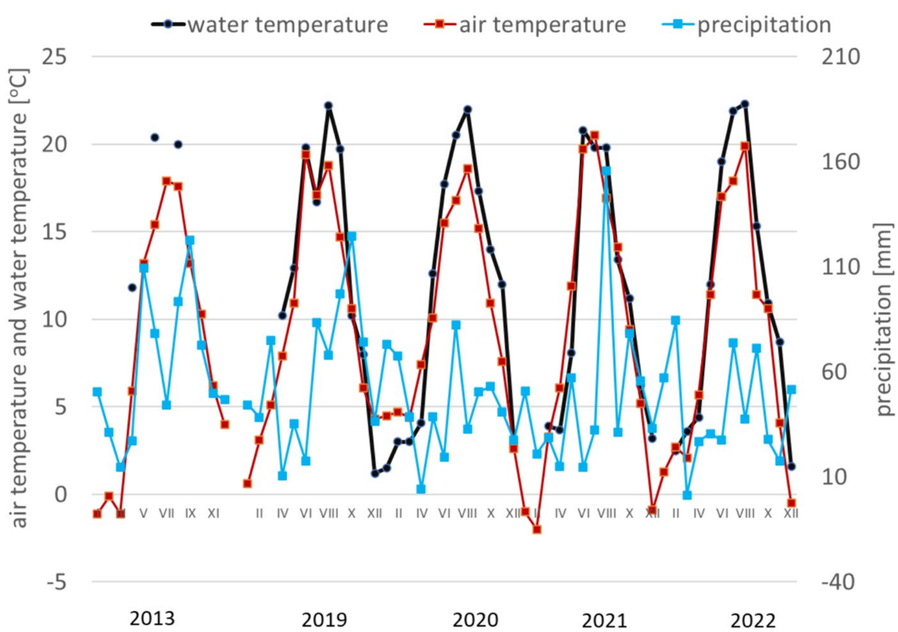


Fig. 2 Water temperature of Mielenko Lake (own measurements) with average monthly air temperature and average precipitation during the research period (according to Łeba meteorological station measurements at https://meteomodel.pl/dane/srednie-miesieczne/?imgwid=354170120&par=tm&max_empty=0)

region (Kashubian Lake District) is above 600 mm H_2O, and the average annual air temperature is 8.6 ^{o} C (Fig. 2, Tomczyk and Bednorz 2022). The average temperature of the winter months in the last 30 years in the Kashubian Lake District was 0.5 ^{o} C, and it was usually negative. The winter of 2019–2020 was much warmer than usual, as the average air temperature values, measured close to Kartuzy City at Łeba meteorological station were between 4.4 °C and 4.7 °C (Fig. 3). Moreover, the 2019 year was the warmest year in the history of measurements in Poland, taking into consideration the period until 2020 (Tomczyk and Bednorz 2022). Probably it led, for the first time in the history of meteorological measurements in Poland, to a complete lack of permanent ice cover not only on the Kartuzy lakes; but also on the other lakes of north-eastern Poland.

Results

Changes in the chemical composition of Mielenko Lake bottom sediment during the research period

The main components of Mielenko Lake bottom sediment were silica and organic matter. with moderate levels of elements binding phosphorus in sediment (iron, aluminum, and calcium) (Table. S1, S2).

In the first year of research (2013) the highest average amount of organic matter was measured (431.55 ± 2.90 mg OM g^{-1} DW in the layer 0–5 cm and 404.50 mg OM g^{-1} DW in the sediment layer 5–10 cm). Directly before restoration (2019) noted average sediment OM concentration was a little lower (401.95 ± 23.55 mg OM g^{-1} DW) in the surficial layer of bottom sediment. But in the first year of phosphorus inactivation (2020), an unexpected decrease in OM content in Mielenko Lake sediment was noted in both sediment layers (to 380.50 ± 8.77 mg OM g^{-1} DW in the layer 0–5 cm and 317.05 ± 0.92 mg OM g^{-1} DW in the deeper layer 5–10 cm) (Table. S1, S2, Fig. 4). But in the next year of restoration (2021) the amounts of organic matter increased in both analyzed sediment layers. After completing restoration procedures organic matter contents in 2022 remained at a similar level, but they were lower compared to the period before restoration. Three-way ANOVA analysis confirmed, that observed changes in OM content were significant (, $F = 4.978$, $p = 0.022$, $df = 9$; Table. 2).

The changes in silica amounts were inversely proportional to organic matter changes. In 2020 the highest mean amounts of silica were noted in

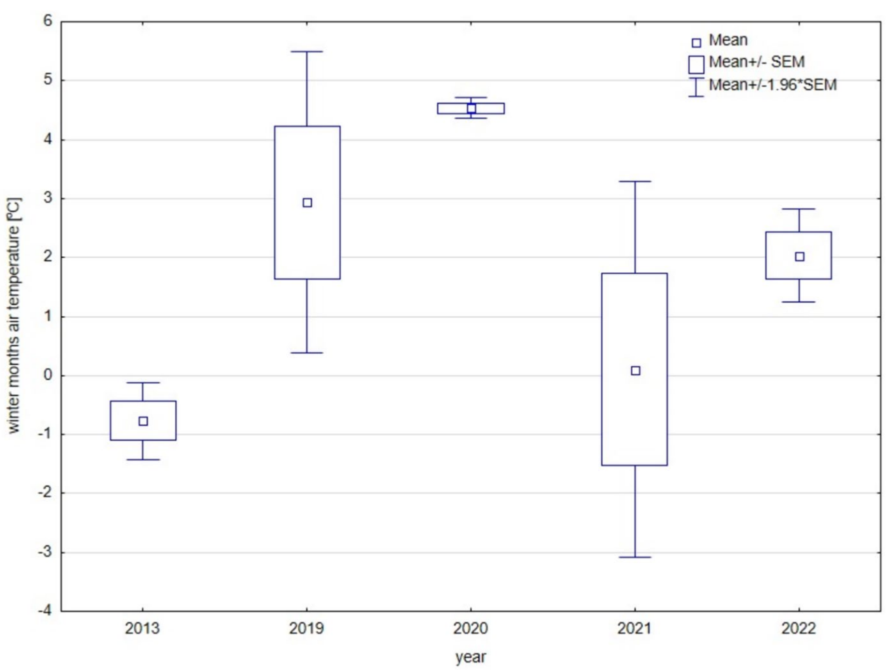


Fig. 3 The changes in average air temperature (winter months) during the research period (based on data from https://meteomodel.pl/dane/srednie-miesieczne/?imgwid=354170120&par=tm&max_empty=0). The differences between years were statistically significant (one-way ANOVA, $F = 4.95$, $p = 0.018$)

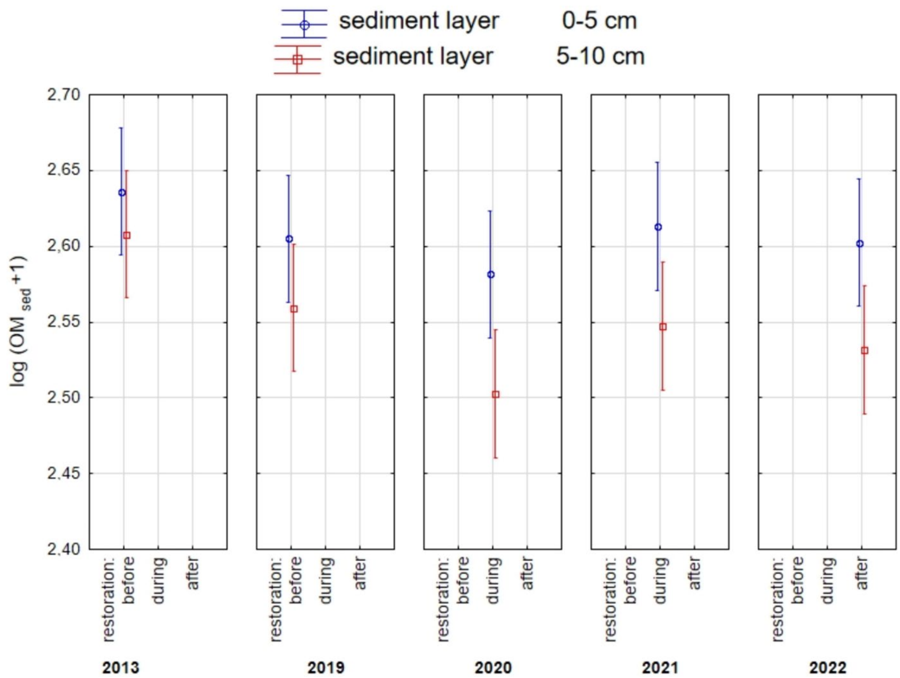


Fig. 4 Changes in organic matter content in the bottom sediment of Mielenko Lake during the research period (annual averages with 0.95 confidence interval, results were log + 1 transformed)

Table 2 Results of the ANOVA analysis of changes in investigated chemical parameters (original results were log + 1 transformed)

Analyzed parameter	Type of ANOVA analysis	Degrees of freedom	F value	P value
Air temperature in winter months	one-way	4	4.95	0.018
Organic matter in sediment	three-way	9	4.978	0.022
SiO_2 in sediment	three-way	9	8.63	0.001
Fe in sediment	three-way	9	3.93	0.02
Al in sediment	three-way	9	12.46	0.0002
Ca in sediment	three-way	9	3.21	0.04
TKN in sediment	three-way	9	4.35	0.016
TP in sediment	three-way	9	17.42	0.00005
NaOH-nrP fraction in sediment	three-way	9	4.13	0.019
BD-P fraction in sediment	three-way	9	Non—significant	
NH_4Cl-P fraction in sediment	three-way	9	4.01	0.02
HCl-P fraction in sediment	three-way	9	12.68	0.0002
res-P fraction in sediment	three-way	9	6.55	0.003
N-NH_4 in the water	three-way	14	32.53	0.000
TKN in the water	three-way	14	11.83	0.000
P-PO_4 in the water	three-way	14	4.18	0.005
Fe in the water	three-way	14	7.19	0.0002
Water transparency	one-way	4	7.26	0.001
Phytoplankton biomass	one-way	4	10.81	0.00006

the analyzed sediment (442.20 ± 5.80 mg SiO_2 g^{-1} DW in the surficial sediment layer 0–5 cm and 505.60 ± 12.30 mg SiO_2 g^{-1} DW in layer 5–10 cm) (Table. S1, S2, Fig. 5). Noted changes were highly

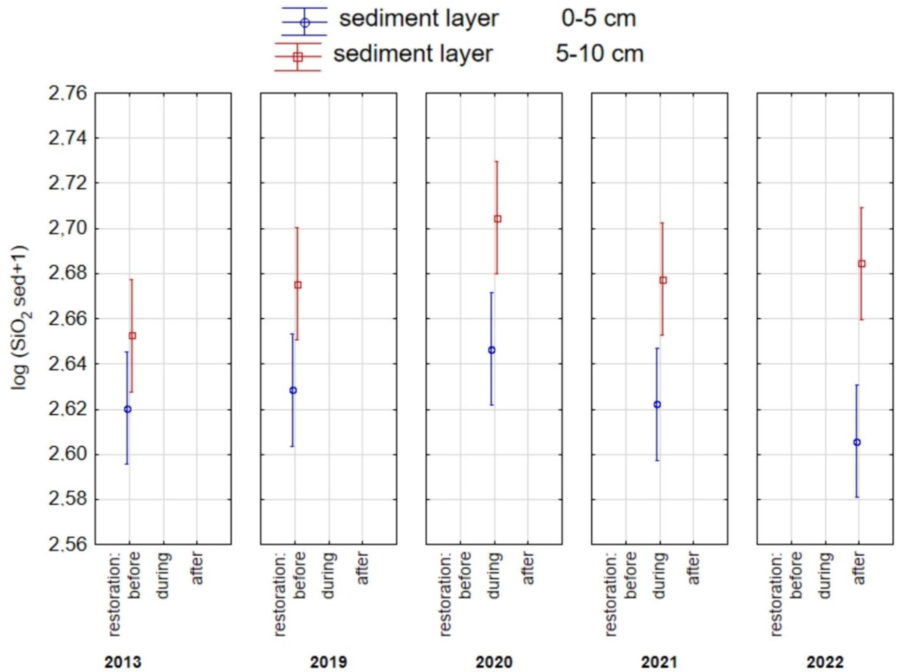


Fig. 5 Changes in silica content in the bottom sediment of Mielenko Lake during the research period (annual averages with 0.95 confidence interval; results were log + 1 transformed)

statistically significant (three-way ANOVA,, F = 8.63, p = 0.001, df = 9, Table. 2).

Mean amounts of iron were the lowest in both analyzed sediment layers in the first research year (2013) (14.67 mg Fe g^{-1} DW -layer 0–5 cm, and 16.77 mg Fe g^{-1} DW – layer 5–10 cm). Phosphorus inactivation treatment using PIX 111 caused a noticeable increase in the Fe sediment content. Maximum iron amounts were observed in the second restoration year (2021) –average Fe

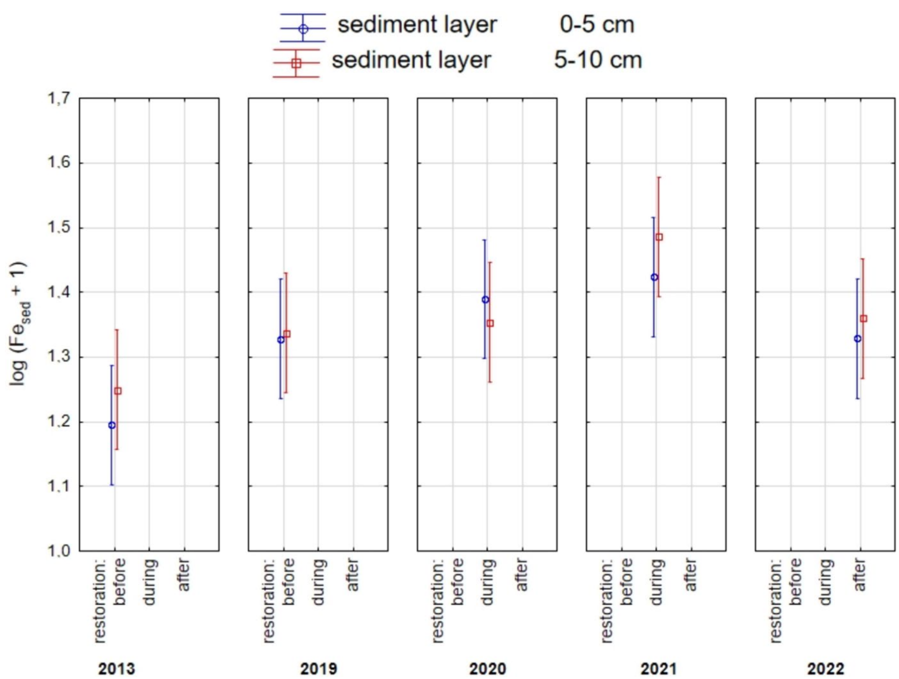


Fig. 6 Changes in iron content in the bottom sediment of Mielenko Lake during the research period (annual averages with 0.95 confidence interval; results were log + 1 transformed)

values amounted to 25.66 ± 4.01 mg Fe g^{-1} DW in the sediment layer 0–5 cm and 29.61 ± 2.08 mg Fe g^{-1} DW in the layer 5–10 cm (Table. S1, S2, Fig. 6). Observed Fe concentration changes were statistically significant (three-way ANOVA –, $F = 3.93$, $p = 0.02$, df = 9, Table. 2).

The average aluminum concentration in the bottom sediment of Mielenko Lake before restoration (2013 and 2019) was in the range between 8.84 ± 1.05 mg Al g^{-1} DW (sediment layer 5–10 cm in 2019) and 9.66 ± 0.79 mg Al g^{-1} DW in the layer 0–5 cm in 2019 as well). Using polyaluminum chloride PAX 18 for phosphorus inactivation procedure (2020–2021) caused the increase in that element content in the sediment. Maximum average amounts of Al were noted in the surficial sediment layer (0–5 cm) – 20.51 mg Al g^{-1} DW in 2022, and in the deeper sediment layer (5–10 cm) in 2021 (20.57 mg Al g^{-1} DW) (Table. S1, S2, Fig. 7). Observed differences between mean Al contents between years were highly significant (three-way ANOVA,, $F = 12.46$, $p = 0.0002$, df = 9; Table. 2).

The changes in calcium concentration in sediment were more clear during the research period in the upper sediment layer (0–5 cm). Before restoration (2013 and 2019) average Ca content in the surficial sediment layer was lower and amounted to 14.54 ± 0.45 mg Ca g^{-1} DW in 2013 and 12.29 ± 0.45 mg Ca g^{-1} DW in 2019. Ca amounts noted in sediment during and after restoration was significantly higher compared to the period before restoration and the maximum Ca amount was observed in 2021 (19.11 ± 1.16 mg Ca g^{-1} DW). In the deeper sediment layer, the highest average level of calcium occurred in 2022 (18.57 ± 1.52 mg Ca g^{-1} DW). (Table. S1, S2, Fig. 8). The calcium changes during the research period were statistically significant (three-way ANOVA,, $F = 3.21$, $p = 0.04$, df = 9; Table. 2).

Total Kjeldahl nitrogen (TKN) amounts changes, which were noted in the sediment of Mielenko Lake during the research period were similar to OM changes. The highest amounts of TKN occurred in the first research year—2013 (26.15 ± 0.21 mg N g^{-1} DW in the layer 0–5 cm and 24.10 ± 2.40 mg N g^{-1} DW). As it was in the case of OM, the lowest average level of TKN was found in 2020 (21.25 ± 0.49 mg N g^{-1} DW in the sediment layer 0–5 cm and 18.25 ± 0.07 mg N g^{-1} DW in the layer 5–10 cm). During the next years, the average TKN concentration rose. (Fig. 9, Table. S1, S2). Observed changes were statistically significant (three-way ANOVA, $F = 4.35$, $p = 0.016$, df = 9; Table. 2).

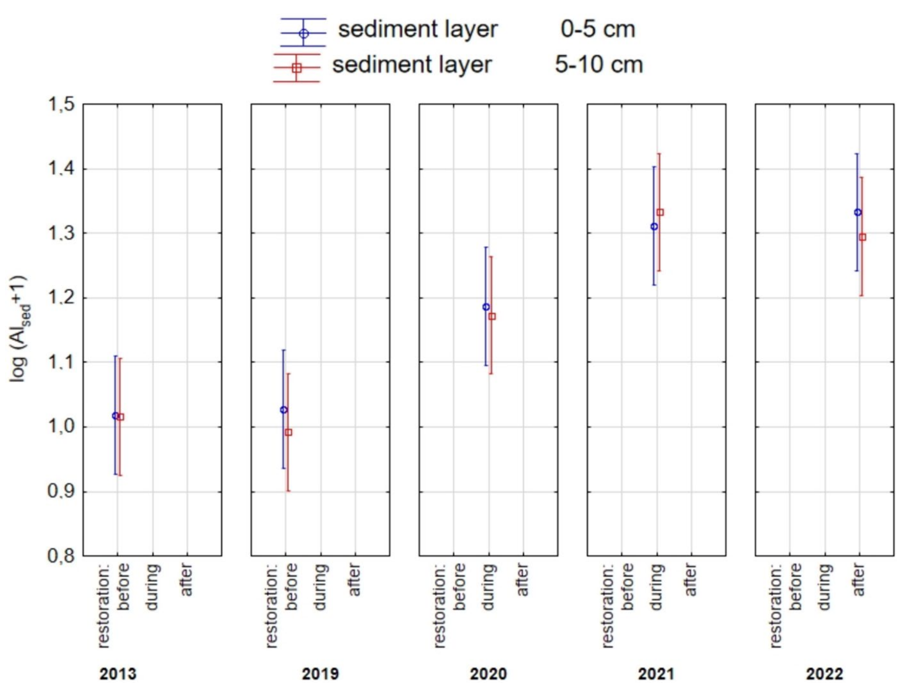


Fig. 7 Changes in aluminum content in the bottom sediment of Mielenko Lake during the research period (annual averages with 0.95 confidence interval; results were log + 1 transformed)

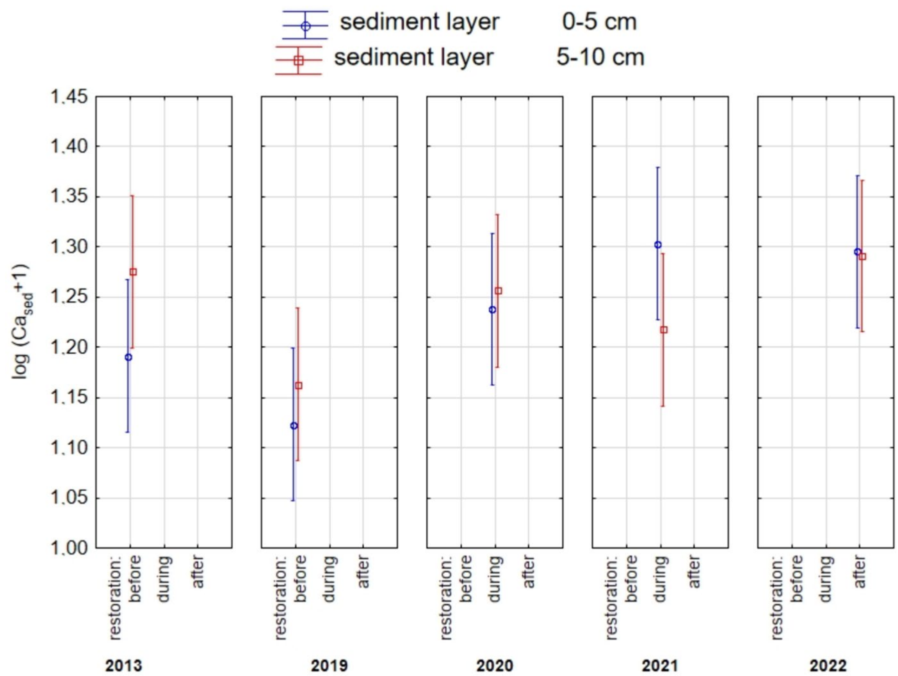


Fig. 8 Changes in calcium content in the bottom sediment of Mielenko Lake during the research period (annual averages with 0.95 confidence interval); results were log + 1 transformed)

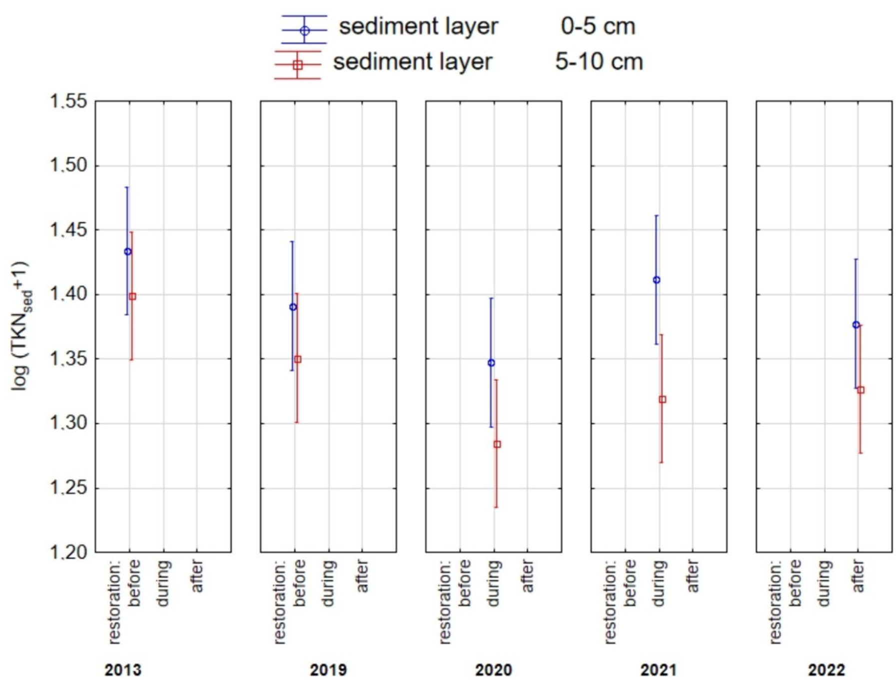


Fig. 9 Changes in nitrogen content in the bottom sediment of Mielenko Lake during the research period (annual averages with 0.95 confidence interval); results were log + 1 transformed)

The analysis of the principal components (PCA), taking into account the correlations between the examined parameters of the chemical composition of the bottom sediments of Lake Mielenko and the average air temperature in the winter months and during the vegetation season, showed an

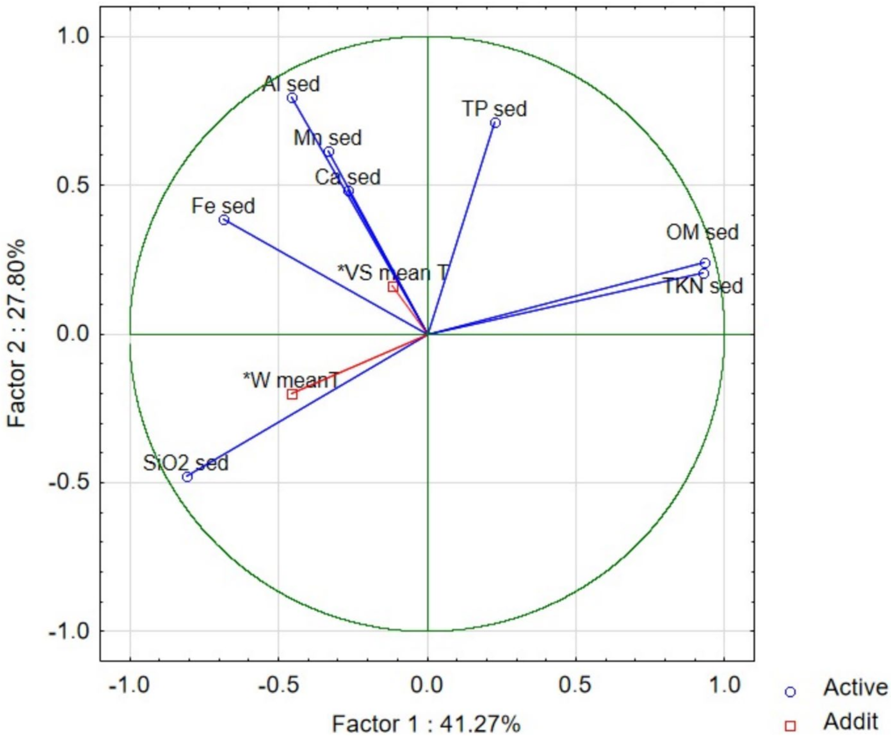


Fig. 10 Results of PCA analysis for bottom sediment components and air temperature during winter and vegetation seasons

existing negative correlation between the average temperature of the winter months and the content of organic matter and nitrogen in the bottom sediments. There was also a positive correlation between the silicate content in the sediment and the average temperature in the winter season (Fig. 10). The first two factors explained a total of 69.07% of the variance.

Phosphorus and its fractions in the Mielenko Lake sediment

The bottom sediment of Mielenko Lake sediment was relatively abundant in phosphorus. In years before restoration (2013, 2019) the TP level was in the range 3.012 – 3.194 mg P g^{-1} DW (sediment layer 0–5 cm) and 2.586 – 3.136 mg P g^{-1} DW (sediment layer 5–10 cm). But after beginning the phosphorus inactivation procedure in 2020, the observed TP concentration in the sediment unexpectedly diminished resulting in the lowest annual level in both analyzed sediment layers during the whole research period (2.206 ± 0.074 mg P g^{-1} DW in the layer 0–5 cm and 2.027 mg P g^{-1} DW in the layer 5–10 cm).

That TP decrease was caused mainly by NaOH-nrP (P bound with organic matter) loss from sediment (to 0.915 ± 0.180 mg P g^{-1} DW on average in 2020). The annual average amounts of that P fraction were 1.672 ± 0.037 mg P g^{-1} DW in 2013 and 1.488 ± 0.093 mg P g^{-1} DW in 2019 for surficial sediment layer 0–5 cm. The decrease in NaOH-nrP amount was noted for sediment layer 5–10 cm as well (from 1.395 ± 0.146 mg P g^{-1} DW in 2019 to 0.703 ± 0.260 mg P g^{-1} DW in 2020) (Table. S3, S4, Fig. 11). Before restoration NaOH-nrP fraction was quantitatively the main P fraction, covering most of sedimentary P (47–50% TP), but its share in TP dropped below 30%TP in the summer of 2020. In 2021, after the next restoration stages, annual average amounts of TP and NaOH-nrP fraction increased. In 2021 and 2022 P bound with organic matter level returned to amounts observed before restoration. Annual sediment TP concentration in 2021 was even higher than its level noted before restoration, but the highest amounts of that element were noted in the last research year (2022) (4.209 ± 0.216 mg P g^{-1} DW in sediment layer 0–5 cm and 4.101 ± 0.148 mg P g^{-1} DW in sediment layer 5–10 cm) (Table. S3, S4, Fig. 11). Observed changes were statistically

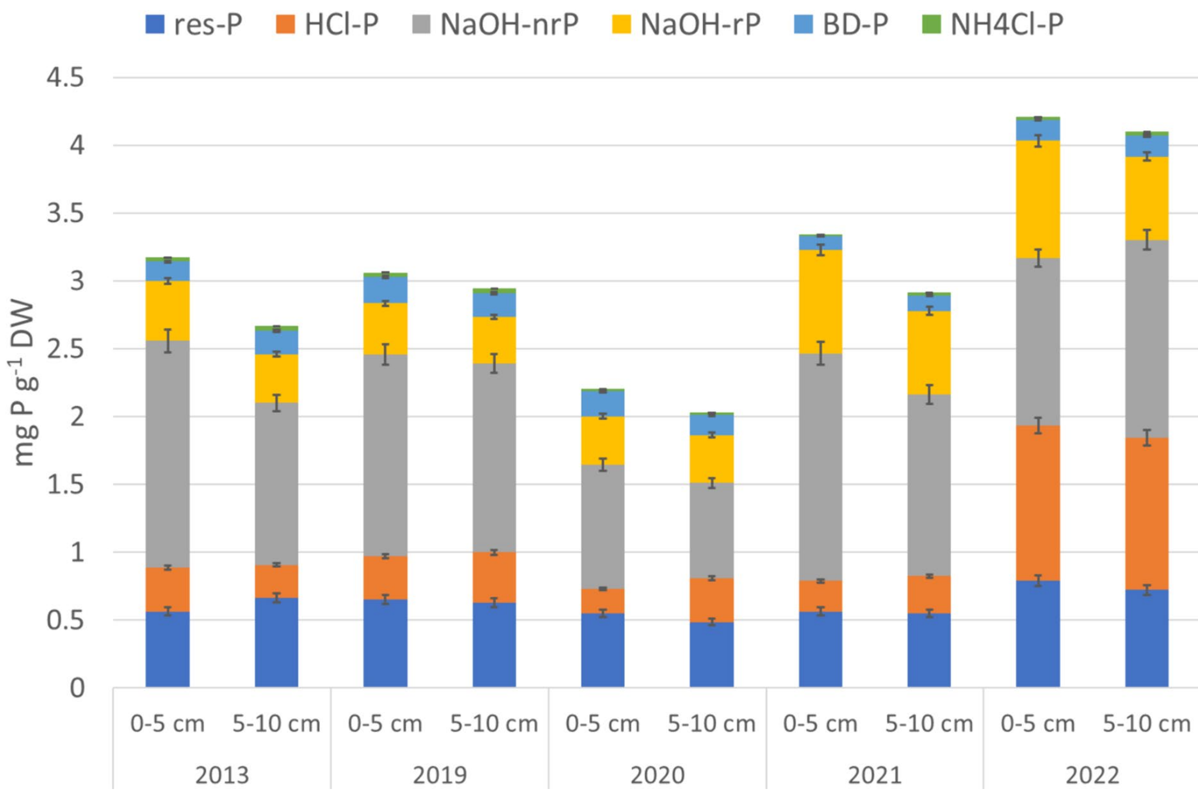


Fig. 11 Changes in phosphorus fractions (mean annual values ± SEM) in both analyzed sediment layers of Mielenko Lake during the research period. The total height of the bars represents the total phosphorus amounts

highly significant (three-way ANOVA, F = 17.42, p = 0.00005, df = 9 for TP and F = 4.13, p = 0.019, df = 9 for NaOH-nrP; Table. 2).

The annual changes in P fraction bound mainly with aluminum and iron oxides and hydroxides (NaOH-rP) showed, that amounts of this P fraction in the first year of research (2013) were a little higher than values noted in 2019 directly before P inactivation. In the first year of restoration (2020) the amount of NaOH-rP did not increase, as it was expected using this lake restoration method. But the percentage of this P fraction in the TP increased from ca.11%TP before restoration to 15–20%TP after lake treatment began. During the next year of restoration (2021) the increase in NaOH-rP fraction amount was much clear (to 0.765 ± 0.171 mg P g^{-1} DW. The highest NaOH-rP annual value was observed after the completion of P inactivation (0.866 ± 0.042 mg P g^{-1} DW in the surficial sediment layer 0–5 cm) (Table. S3, S4, Fig. 11), and its percent share in TP exceeded 22%TP. Noted NaOH-rP changes were highly significant (three-way ANOVA,, F = 10.17, p = 0.001, df = 9; Table. 2).

Using the iron coagulant PIX 111 for P inactivation did not significantly influence the BD-P fraction (P sensitive for redox potential, mainly bound with Fe and Mn) changes in the analyzed bottom sediment of Mielenko Lake. Before restoration (2013 and 2019) mean annual values of that fraction amounted to 0.144 ± 0.017 mg P g^{-1} DW and 0.195 ± 0.016 mg P g^{-1} DW in the layer 0–5 cm, and 0.171 ± 0.004 mg P g^{-1} DW and 0.174 ± 0.074 mg P g^{-1} DW, respectively. After beginning the restoration in 2020 and in the next 2021 year amounts of this fraction were lower than before restoration, with minimum values observed in the second year of treatment (2021) in both analyzed sediment strata (0.103 ± 0.015 mg P g^{-1} DW and 0.115 ± 0.053 mg P g^{-1} DW) (Table S3, S4).

Unlike to BD-P fraction, another easy bioavailable P fraction changes (NH_4Cl-P) during the research period were significant (three-way ANOVA, F = 4.01, p = 0.02, df = 9; Table. 2). Before restoration (2013 and 2019) the mean annual concentrations of this P fraction (0.032 mg P g^{-1} DW in the sediment layer 0–5 cm and 0.035 – 0.036 mg P g^{-1} DW in the layer 5–10 cm) were higher compared to the values noted during restoration (2020 and 2021) in both sediment layers (0.020 ± 0.004 mg P g^{-1} DW and 0.008 ± 0.004 mg P g^{-1} DW in the surficial sediment, as well as 0.018 ± 0.001 mg P g^{-1} DW and 0.019 ± 0.009 mg P g^{-1} DW in the deeper sediment layer, respectively). After the completion of restoration treatment, the noted amounts of NH_4Cl-P increased but remained lower than before treatment in both analyzed sediment layers (Fig. 11, Tables S3, S4).

The hardly bioavailable (HCl-P) sediment P fraction, as well as res-P, which represents P buried in sediment concentrations before restoration (2013 and 2019) quantitatively were the second (res-P) and fourth or third (HCl-P) P fractions in the total amount of this element in analyzed sediment. Their concentration changes during the research period had different directions from the other P fractions, and the changes looked different in both analyzed sediment layers. P inactivation caused a noticeable decrease in both P fractions. The minimum annual mean value of HCl-P was noted in 2020 in the layer 0–5 cm (0.183 ± 0.149 mg P g^{-1} DW), while in 2021 – in the sediment layer 5–10 cm (0.277 ± 0.016 mg P g^{-1} DW). The lowest level of res-P fraction was noted in the first year of restoration (2020) (0.548 ± 0.067 mg P g^{-1} DW in the layer 0–5 cm, and 0.485 ± 0.015 mg P g^{-1} DW in the sediment layer 5–10 cm). In the last year of research both fractions amounts in sediment increased to the highest level observed during the whole research period (HCl-P—1.145 ± 0.396 mg P g^{-1} DW and 1.123 ± 0.326 mg P g^{-1} DW for layers 0–5 cm and 5–10 cm, respectively; res-P – 0.791 ± 0.049 mg P g^{-1} DW and 0.723 ± 0.045 mg P g^{-1} DW for layers 0–5 cm and 5–10 cm, respectively) (Fig. 11, Tables S3, S4). Observed changes were highly significant (three-way ANOVA, df = 9, F = 12.68, p = 0.0002 for HCl-P; and df = 9, F = 6.55, p = 0.003 for res-P; Table. 2).

The principal components analysis (PCA), which was aimed at detecting the relationship between the content of particular phosphorus fractions and the average air temperature in the winter months and

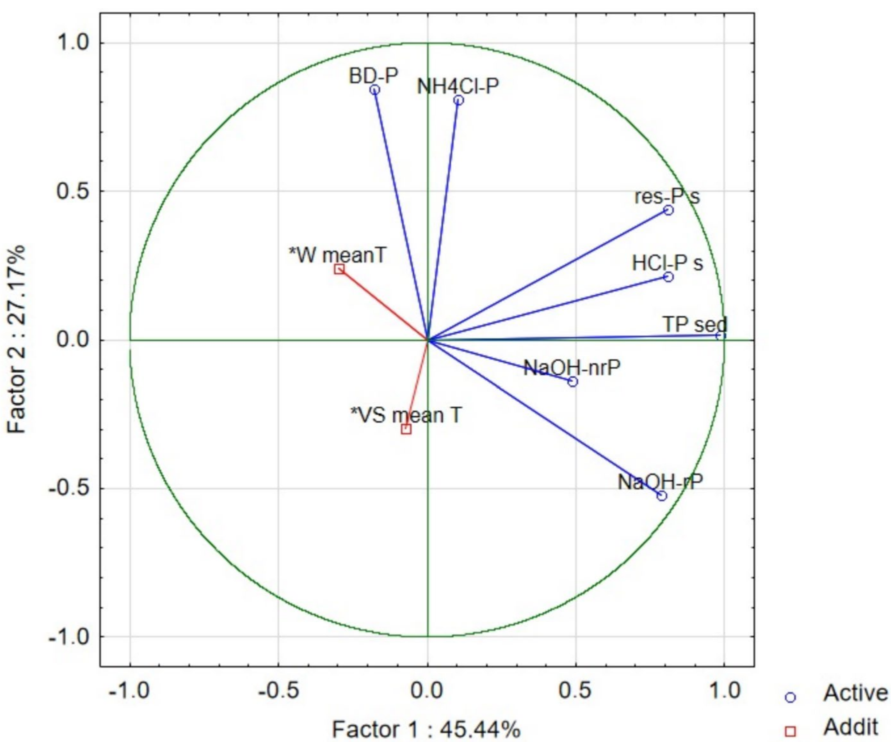


Fig. 12 PCA analysis results for phosphorus fractions and air temperature during winter and vegetation seasons

during the growing season, showed the existence of a clear negative correlation between the content of the NaOH-nrP fraction (phosphorus bound to organic matter) and the average air temperature in the winter season (Fig. 12). The first two factors explained a total of 72.56% of the variance.

Near-bottom and pore water of water–sediment interface

Maximum TKN and TP amounts were noted in the summer season (3.96 ± 0.352 mg TKN dm^{-3} and 1.51 ± 0.112 mg TP dm^{-3} in near-bottom water; 18.66 ± 1.232 mg TKN dm^{-3} and 1.72 ± 0.212 mg TP dm^{-3} in interstitial water, layer 5–10 cm) (Figs. 13 and 14). In 2019, the observed annual average nutrient concentration was at a similar level to the first year of observations (2013) (Tables S5, S6, S7). But first applications of PAX 18 and PIX 111 (2020) to the Mielenko Lake water did not cause the expected decrease in mineral P amounts in the near-bottom water and interstitial water in the surficial sediment layer (0–5 cm) (Fig. 14). That effect was observed during the second year of research, after consecutive PAX 18 and PIX 111 dosing (Fig. 14). The lowest annual average TP and P-PO_4 values were observed in

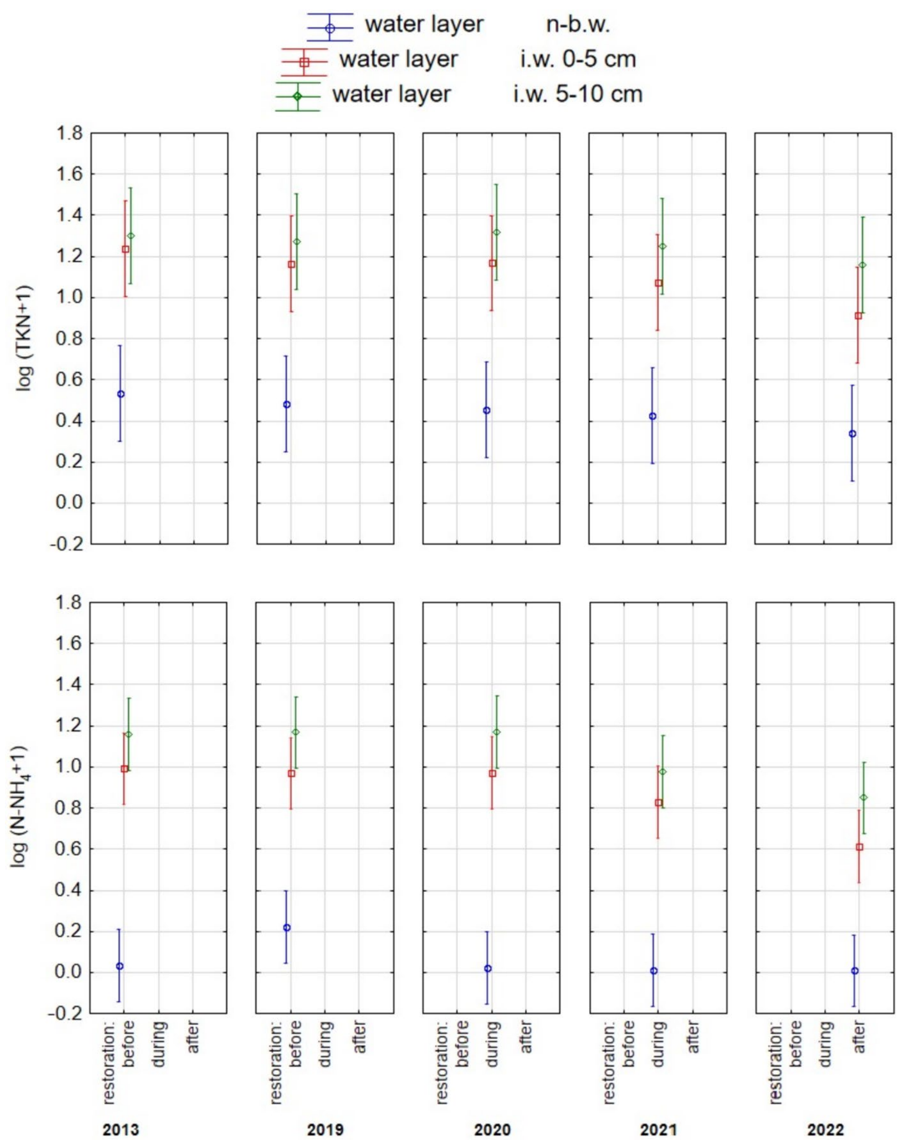


Fig. 13 Changes in TKN (upper graph) and ammonia (lower graph) annual averages with 0.95 confidence interval, observed in near-bottom and interstitial water of Mielenko Lake during the research years (results were log + 1 transformed)

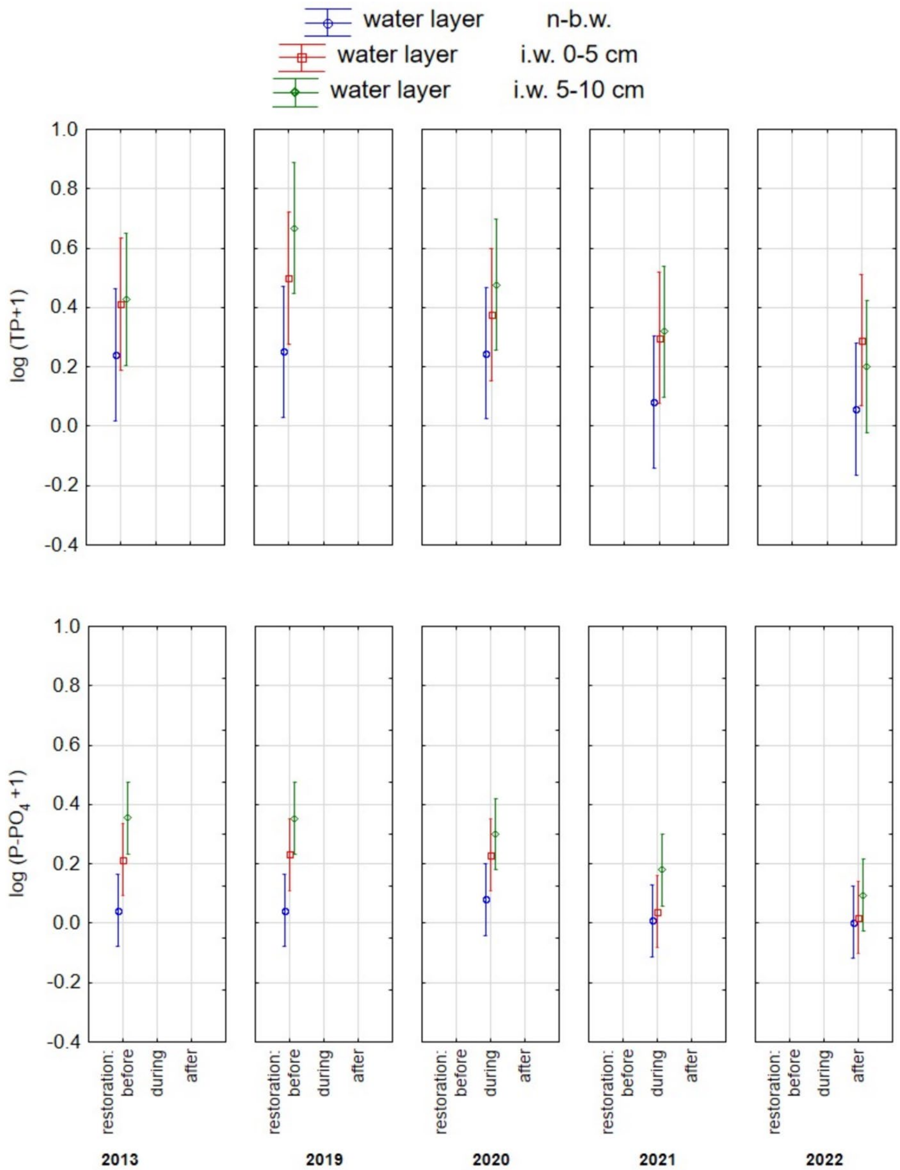


Fig. 14 Changes in TP (upper graph) and P-PO_4 (lower graph) average annual concentrations with 0.95 confidence interval observed in near-bottom and interstitial water of Mielenko Lake during the research years (original values were log + 1 transformed)

2022, after the termination of restoration procedures (0.008 ± 0.003 mg P-PO_4 dm^{-3} and 0.142 ± 0.054 mg TP dm^{-3} in the near-bottom water; 0.047 ± 0.062 mg P-PO_4 dm^{-3} and 1.036 ± 0.820 mg TP dm^{-3} in the water layer 0–5 cm; 0.251 ± 0.184 mg P-PO_4 dm^{-3} and 0.590 ± 0.113 mg TP dm^{-3} in the layer 5–10 cm) (Fig. 13). Also, the nitrogen compounds' average level was the lowest in 2022 (Fig. 13, Tables S5, S6, S7). Observed changes in nitrogen concentration were statistically significant (three-way ANOVA: N-NH_4: $F = 32.53$, $p = 0.000$; TKN: $F = 11.83$, $p = 0.000$, $df = 14$, Table. 2), while only changes in phosphate concentration were significant (P-PO_4: $F = 4.18$, $p = 0.005$, $df = 14$, Table. 2).

Despite of fact, that PIX 111 (iron chloride) was used for lake restoration, a clear increase in Fe concentrations was not observed in the analyzed water strata. In the near-bottom water Fe annual average concentration noted in the first year of restoration (0.500 ± 0.079 mg Fe dm^{-3} in 2020) was only a little higher, than the 2013 annual average Fe amount (0.480 ± 0.057 mg Fe dm^{-3}). In the next two years, the lower Fe annual amounts were noted (0.232 ± 0.014 mg Fe dm^{-3} on average

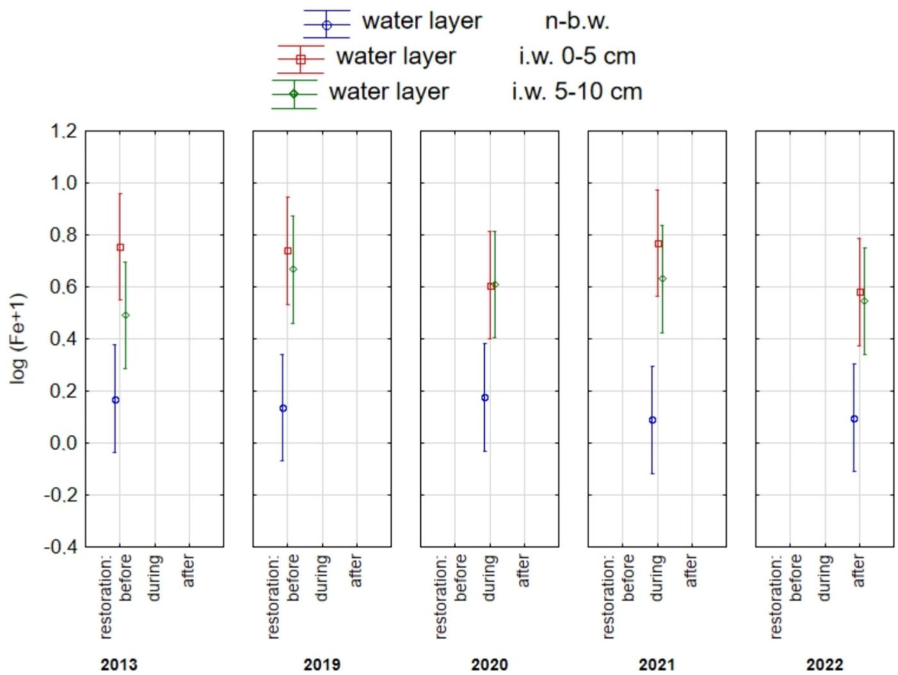


Fig. 15 Changes in iron average annual concentrations with 0.95 confidence interval observed in near-bottom and interstitial water of Mielenko Lake during the research years (original values were log + 1 transformed)

in 2021). In the interstitial water, the decrease in the iron concentration was noted in the layer 0–5 cm, from 4.750 ± 1.202 mg Fe dm^{-3} in 2013 to 2.875 ± 0.255 mg Fe dm^{-3} in 2021. Higher annual Fe values during the restoration were noted in the deepest analyzed sediment layer (5–10 cm)

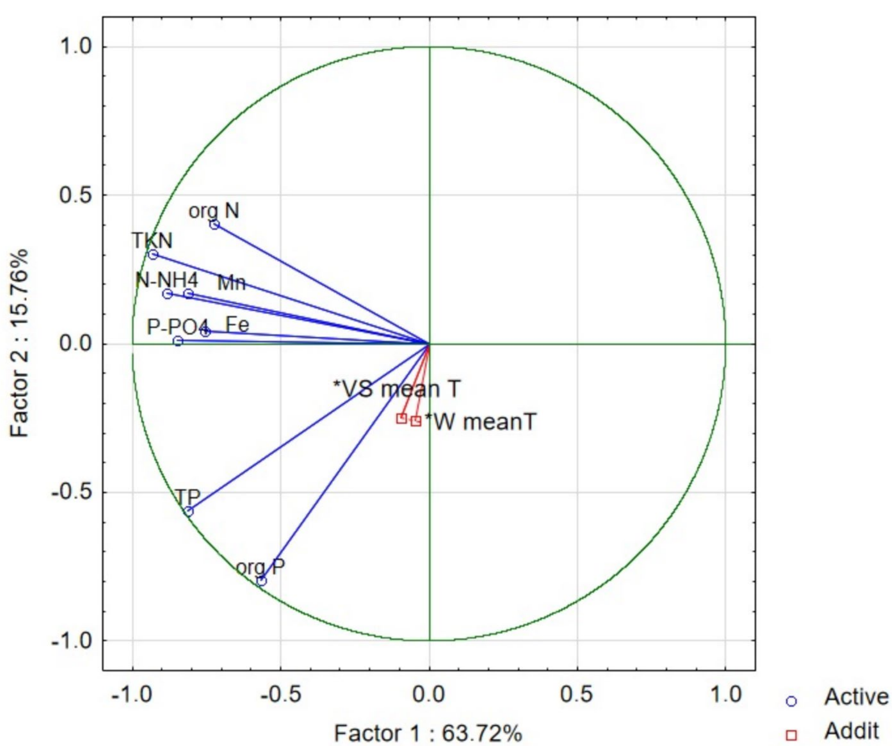


Fig. 16 PCA results – relations between the chemistry of the water medium of the water–sediment interface of Mielenko Lake and the air temperatures in winter and vegetation seasons

(Fig. 15, Tables S5, S6, S7) Observed annual average concentration changes were statistically significant (three-way ANOVA, $F = 7.19$, $p = 0.0002$, $df = 14$; Table 2).

Principal components analysis (PCA) didn't show direct significant correlations between analyzed chemical compounds of the water medium of the water–sediment interface and air temperature in winter and vegetation seasons (Fig. 16).

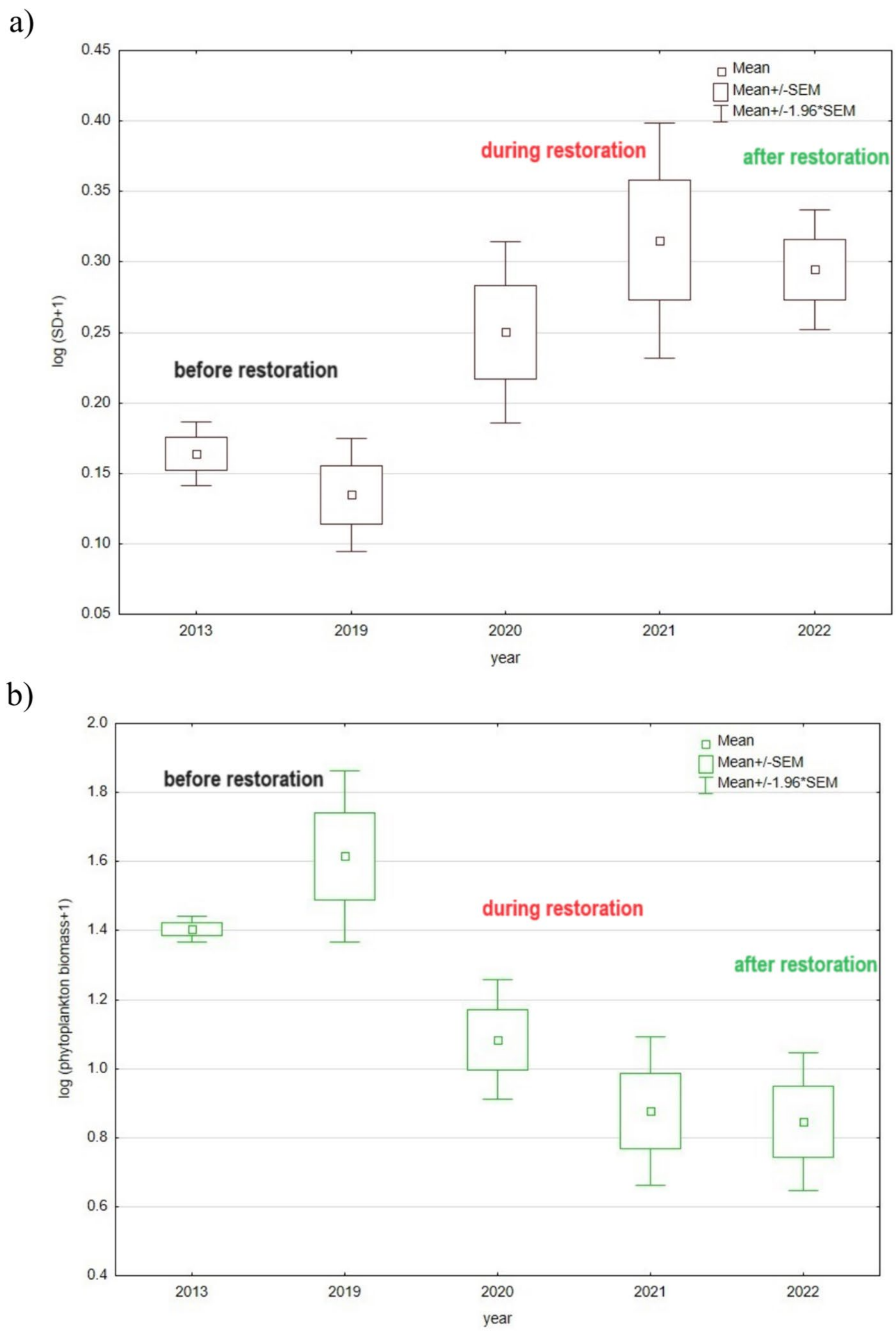


Fig. 17 Changes in Secchi disc visibility (**a**) and phytoplankton biomass (**b**) (in Mielenko Lake during the research period (original values were log + 1 transformed)

Water transparency changes and phytoplankton biomass

The water transparency in the years before lake restoration (2013 and 2019) was rather low – average annual values amounted to 0.46 ± 0.089 m in 2013 and 0.37 ± 0.148 m in 2019. In the first year of restoration, the water transparency improved, but its lowest value observed during vegetation season amounted to 0.5 m only (Table S8). But in the next year P inactivation brought an improvement in water transparency, resulting in the highest mean value of this parameter (1.22 ± 0.487 m). After completing restoration measures on Mielenko Lake annual mean water transparency still was higher, compared to the years before restoration (Fig. 17, Table S8). Observed changes were highly significant (one-way ANOVA, $F = 7.26$, $p = 0.001$, $df = 4$; Table 2).

Changes in water transparency were negatively correlated with phytoplankton biomass. In the first year of research (2013) average phytoplankton biomass was rather high (24.44 ± 2.284 mg dm^{-3}. In 2019 the values of this parameter were almost doubled (49.67 ± 42.743 mg dm^{-3}), because of extremum high biomass amounts noted during the summer season (up to 125.41 mg dm^{-3}). However, after beginning the phosphorus inactivation procedure in 2020 annual average phytoplankton biomass dropped to 12.01 ± 4.701 mg dm^{-3}. This downward trend was observed in the next research years, and the lowest average biomass value was noted in 2022 (6.71 ± 3.143 mg dm^{-3}) after the termination of restoration measures (Fig. 17, Table S8).

Assessment of exchange of P and N in the water–sediment interface

Taking into consideration the deepest part of an active bottom area below isobath 1.5 m, we assessed the amount of TP and TN released since the period 2019–2020 by bottom sediment (173.9 kg TP and 567.0 kg TN from both analyzed sediment layers) (Table 3), After the first dosing of coagulants in 2020 1.3 kg P only was bound in the sediment (the deeper sediment layer), but the P release from both NaOH extractable fractions was present. The release of NaOH-nrP fraction was much higher and it was not possible to bind all this load by coagulant dosing. Next PAX 18 and PIX 111 doses applied in 2021 were able to bind more P in the sediment as NaOH-rP (direct binding with Al and Fe hydroxides and oxides) and NaOH-nrP (P bound with organic matter) fractions. After completing the treatment total pool of P directed to sediment amounted to 198.0 kg TP (including 65.4 kg P bound as NaOH-rP, and 136.8 kg P -as NaOH-nrP, in both sediment layers). In 2022 the type of P binding by sediment was different – more of P was stored as hardly bioavailable HCl-P and res-P (Fig. 18).

Discussion

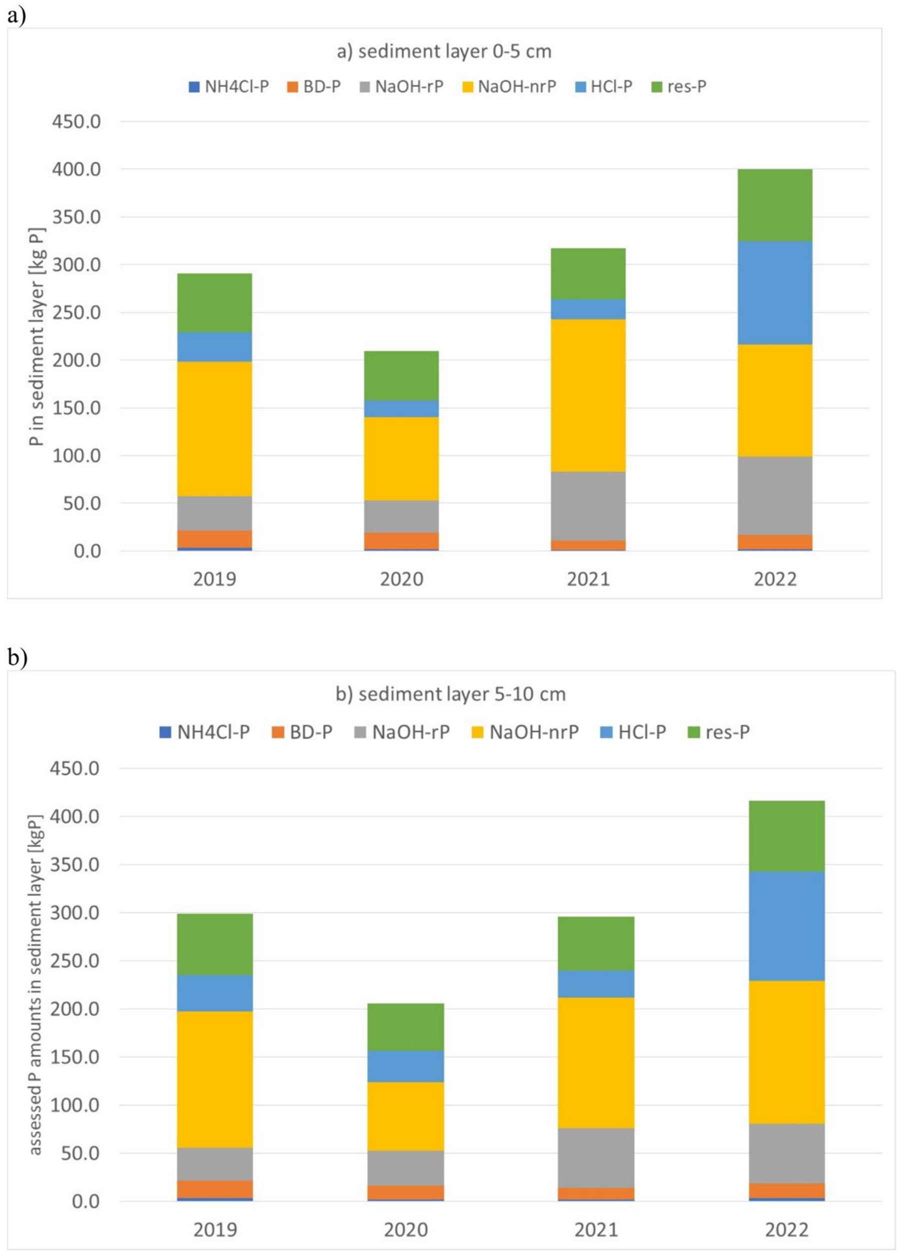
The influence of restoration on nutrients concentration in the water–sediment interface

Lakes located inside the human settlements face very strong anthropopressure. Among many factors influencing water quality, the most serious threat to urban lakes is the raw sewage inflow from point sources. Excessive eutrophication is also favored by higher values of Schindler's coefficient (the ratio

Table 3 Assessed average annual amounts of TP and TKN (in kg) and difference (in kg) between consecutive years for the deepest area (below 1.5 m) of Mielenko Lake

Sediment components	Sediment layer	Mean annual amount (in kg)				A balance between years (in kg)		
		2019	2020	2021	2022	2019/2020	2020/2021	2021/2022
TP	0–5	290.7	209.6	317.9	400.0	− 81.1	108.2	82.1
	5–10	298.5	205.7	295.4	416.1	− 92.8	89.8	120.6
TN	0–5	2252.2	2019.4	2356.7	2171.4	− 232.8	337.4	− 185.3
	5–10	2186.4	1851.6	2014.0	2049.5	− 334.8	162.3	35.5

Fig. 18 Assessed average annual amounts of P (in kg) for the deepest area (below 1.5 m) of Mielenko Lake (**a** sediment layer 0–5 cm; **b** sediment layer 5–10 cm)



of the sum of the lake area and its catchment area to lake water volume), illustrating the impact of the catchment area on the water quality of the water body. The value of this coefficient for Lake Mielenko is unfavorable (37.88) (Grochowska et al. 2019), but it is balanced by the type of catchment use (absence of diffused agricultural sources of pollution). During our research, the main problem in external loading was mineral pollution from the road salt storage area, which increased the Mielenko Lake water salinity (Grochowska et al. 2022). Values of external nutrient load estimated in 2013 (0.22 g P/m^2 year and 2.638 g N/m^2 year) exceeded critical nutrient loads (assessed using Vollenweider criteria (Grochowska et al. 2019, Vollenweider 1976). This could explain the turbid state of water in that lake, with phytoplankton dominance before restoration. External nutrient loading was reduced before restoration (to the level

0.081 g P/m^2 year and 1.791 g N/m^2 year), mainly by decreasing used amounts of ground baits by anglers, and it is below the critical P load threshold now (Grochowska et al. 2019), which was a necessary measure before restoration.

Human activity around lakes can enhance the bottom sedimentation rates. Baud et al (2021) found, that sediment accumulation rates and mass accumulation rates are rising with global human population increasing. Usually the sedimentation rate in eutrophic lakes can be higher than several mm y^{-1}. In shallow lakes, those values can be higher than in deep, stratified lakes, and can exceed value 10 mm y^{-1} (Xu et al. 2017). Values assessed by Baud et al. (2021) even reached values higher than 30 mm y^{-1} in the period since 1963 AD. Because Mielenko Lake is shallow, urban lake, then sedimentation rates could be rather higher. Taking into consideration the theoretical values of sedimentation rate for shallow, eutrophic lake, the resolution of our sampling (5 cm thick sediment upper layer) was rather rough, and hence observed changes can show more than one year processes. But during the research, changes in the chemical composition of sediments and near-bottom and pore water were observed throughout the entire 10 cm surface layer of sediments, which confirms the view of many authors (Boström et al. 1988; Søndergaard et al. 2003; Augustyniak 2018) that the layer of active substance exchange in shallow lakes reaches lower than the strictly surface layer of sediments'. In Mielenko Lake, biomanipulation removed sediment resuspending cyprininds, such as carp, that may disturb sediment to more than 15 cm deep (Huser et al. 2016), yet the changes in sediment chemistry observed support the view that in shallow lake areas, many factors may favor more dynamic exchange processes (Sheffer 2004). In addition, when there is a shift in primary production from phytoplankton to macrophytes, this can result in very rapid changes in the chemical composition of the sediments.

Quite intensive primary production processes in Mielenko Lake and its alimentation by humic substances from the forest part of the catchment led to high organic matter concentration (exceeding 400 mg g OM g^{-1}DW) in the bottom sediment in the deepest part of the lake, despite rather good conditions for organic matter mineralization processes during vegetation season.

The first analyses of near-bottom and interstitial water, performed in 2013, revealed that Mielenko Lake nutrient levels in the near-bottom and pore water were characteristic of eutrophic lakes (Tables S5, S6, S7, Figs. 13, 14, 15). Assessed TP and TN internal loads in the period 2019–2020 were much higher than external loading. That situation is often common for shallow lakes, especially for water bodies with a pollution legacy deposited in sediment (Abell et al. 2020; Carvalho et al. 2012; Scheffer 2004). For those lakes, planned restoration methods should focus on the internal loading decrease (Abell et al. 2020). Only a reduction of external nutrient loads could not be sufficient to obtain demanded water quality improvement. The results of our research performed in 2019, confirmed the turbid state of Mielenko Lake, with low water transparency and high phytoplankton biomass (Table S8, Fig. 17). The sediment's role in P-cycling, and thus – in controlling harmful algal blooms in the shallow lake was also described by Randall et al. (2019). They maintain, that P legacy, present in the sediment, can be a serious source for potential algal blooms.

The first year of coagulant application (2020) did not show very clear positive changes in the analyzed water–sediment interface of Mielenko Lake (eg. Figure 13, 14), but the first effect was observed for lake water only (Fig. 17). The mean values of phytoplankton biomass and water transparency changed, showing the improvement of water quality in lake. The reduction in the availability of phosphorus in the lake water for phytoplankton primary producers was much more pronounced in the following year of restoration (2021). Here, a reduction in phytoplankton biomass and an improvement in water transparency were observed, which was accompanied by an increase in the content of organic matter in the sediments, and an increase in the content of phosphorus and nitrogen. The amount of sedimentary phosphorus increased, mainly due to an increase in the fraction of phosphorus associated with organic matter (NaOH-nrP) and aluminum and iron oxides and hydroxides (NaOH-rP), which was undoubtedly the result of restoration activities. At the same time, it is worth noting that no clear trends were observed in the amount of phosphorus fraction sensitive to changes in redox potential (BD-P). It seems that the lack of a significant increase in the amount of this fraction as a result of the use of the

PIX 111 coagulant is the phenomenon described by Rydin and Welch (1998) and Rydin (2000), who stated that after the use of an aluminum coagulant, the phosphorus bound in the BD-P fraction gradually turns into the NaOH-rP fraction. Under rather good aerobic conditions prevailing in the shallower parts of polymictic lakes and with sufficient alkalinity of the water, the dosed iron preparation is easily hydrolyzed to form iron (III) hydroxide, which binds phosphates present in the lake water and the overlying waters. In the case of reducing the redox potential in the water–sediment interface, aluminum (III) hydroxide, which is also a product of the hydrolysis of the aluminum coagulant, will bind the phosphorus pool released from the BD-P fraction.

Increasing the transparency of the lake's water, in turn, brought about a fairly rapid qualitative change in the lake's vegetation. The improvement of light conditions resulted in a rapid expansion of the macrophyte range. Already in 2021, underwater meadows of plants of the pondweed species—*Potamogeton crispus* L, *Potamogeton natans* L., developed very intensively, and the previously absent species *Potamogeton lucens* L. appeared (Grzybowski 2022; Tandyrak 2022, Photo 1). Improving water transparency may allow shallow lakes to become clear water, dominated by macrophytes, which can effectively compete with phytoplankton for nutrient resources and maintain good water quality (Hilt et al. 2017). This is the phenomenon we observed in Lake Mielenko after implementing the P inactivation procedure.

The step-off of phytoplankton from the role of the dominant primary producer also had an impact on the chemical composition of bottom sediments in the studied lake. In the examined sediments, an increase in the content of calcium was observed, as well as an increase in the deposition of phosphorus in the form of hardly bioavailable HCl-P and res-P fractions. This effect was even more pronounced after the restoration was completed—in 2022, the amount of phosphorus in the HCl-P fraction was equal to the amount of phosphorus associated with organic matter (NaOH-nrP). The reason for the increase in calcium content in the water of Lake Mielenko could be the increase in the inflow of calcium with rainwater in recent years, coming from the storage area of anti-ice ice agents (Grochowska et al. 2022). This could additionally favor the development of macrophytes of the genus *Potamogeton*, which are calciphilous plants. According to archival research by Riemer and Toth (1969), plant tissues of the genus Potamogeton may contain up to 20% calcium. After fruiting, these plants die and decompose, in the next growing season they grow back from seeds and rhizomes. Therefore, it seems likely that a large biomass of easily decomposing macrophytes, rich in calcium, may contribute to an increase in the content of this element in bottom sediments, as well as to an increase in the amount of phosphorus bound in NaOH-nrP, HCl-P, and res-P fractions. Since the hardly bioavailable calcium-bound phosphorus fraction (HCl-P) and the res-P fraction, which is practically biologically inaccessible, bind phosphorus in bottom sediments very permanently (Bańkowska et al. 2020), the quantitative increase in the share of these fractions in the total phosphorus contained in sediments should also contribute to the reduction of internal loading in Lake Mielenko. The deposition of calcium and the fraction of phosphorus bound to it is affected by pH and temperature (Augustyniak 2018, Bańkowska et al. 2020), however, in the analyzed sediment in 2021 and 2022, no significant reduction in the content of fractions extracted with NaOH solution was observed (NaOH-rP and NaOH – nrP). Hence, it can be assumed that the pH in the water–sediment interface did not increase beyond the range where phosphorus is released from these fractions.

The interesting fact of reducing the concentration of nitrogen compounds in the water–sediment interface during the research period was also observed. Many studies on the method of phosphorus inactivation show that this method does not have a significant impact on the nitrogen content in the water of restored lakes (Grochowska and Brzozowska 2015). On the other hand, our research shows a decrease in the concentration of nitrogen compounds in the water-sediments interface, more visible in the last two years of research. This coincides with the massive development of macrophytes in Lake Mielenko. Therefore, it seems possible that growing macrophytes effectively absorb nitrogen compounds from pore water, and this phenomenon is the reason for the observed changes in nitrogen content in the studied layers of water medium of the water–sediment interface. In addition, sediment-rooted macrophytes can act as an oxygen pump, releasing oxygen into the sediment through the roots (Brix 1993). The presence of aerobic and anaerobic niches in the sediments next to each other may favor the processes of coupled nitrification–denitrification (Risgaard et al. 1994, Augustyniak 2018) and increase the emission of molecular nitrogen from the sediments. According to Gibbs et al. (2011) alum addition to lake sediment can enhance nitrification and denitrification processes in the sediment in aerobic conditions.

The beginning of phosphorus inactivation in 2020 prevented a significant deterioration of the water quality of Mielenko Lake; because in the case of such significant amounts of nutrients released from sediments in the 2019–2020 season, the turbidity of water with a huge amount of phytoplankton biomass would certainly be strengthened. However, inactivation helped to limit the development of phytoplankton, achieve good water transparency in Mielenko Lake, and transfer the burden of primary production to macrophytes, which will certainly improve the ecological status of this lake. However, Abell et al. (2020) mention that the massive presence of macrophytes can cause some problems with macrophyte senescence after completing an annual life cycle. Also after the shift from turbid into clear water, newly established biocenosis has less biodiversity, than originally clearwater lake ecosystems (Hilt et al. 2017).

Direction of changes in nutrient amounts of Mielenko Lake induced by lack of the permanent ice cover during winter season

Synergism between warming and re-eutrophication following phosphorus inactivation can increase internal loading in lakes (Kong et al. 2023; Moss et al. 2011). Shallow polymictic lakes are specific lake ecosystems. They function differently from deeper lakes, which develop thermal stratification. First of all, they are much more susceptible to degradation (Abell et al. 2020; Scheffer 2004).

Primary production of shallow polymictic lakes in temperate climate zone usually substantially slowed down during the winter season due to the presence of winter ice cover. It limits production because of decreasing light penetration to the production zone. Transparent ice cover gives a possibility to light penetration to the water layer under the ice to maintain production, but very often that phenomenon is limited by snow cover laying on the ice surface (Leppäranta 2015). Also, low water temperature under ice is an important factor limiting the rate of primary production processes. In the past, the time of ice cover existing for lakes in Poland was rather long, ca. 100 days for Northern Poland. But similarly to other temperate regions, the duration of ice cover on Polish lakes is continuously getting shorter due to climate changes (Marszelewski and Skowron 2006).

During the exceptionally warm winter of 2019/2020 without ice cover, water mixing and relatively good aerobic conditions enabled the continuity of primary production, as well as the mineralization of organic matter, combined with the release of nutrients from bottom sediments. Of course, at a lower temperature, these processes were certainly slower, but they were not as severely limited as if the lake had been covered with ice for a longer time. With the increase in temperature in the spring of 2020, the processes of mineralization of organic matter in the surface layer of sediments were accelerated, but the primary production of the reservoir was limited as a result of the first dosing of coagulants at the turn of February and March. There was no noticeable increase in the phosphorus content in the bottom sediments, and the recorded amount of total phosphorus in the sediments decreased significantly during 2020. The only possible explanation for this situation is a much more intensive mineralization of organic matter in the sediments, which was observed during the research, as well as confirmed by a decrease in the amount of phosphorus bound to organic matter (NaOH-nrP) and total nitrogen. Nitrogen in sediments is deposited mainly in the form of organic matter (Augustyniak 2018), hence the fluctuations in its content in sediments are correlated with fluctuations in the content of organic matter. The results of the principal components analysis (PCA) revealed significant negative correlations between air temperature in the winter season and OM, TKN, and P fraction bound with organic matter (NaOH-nrP) (Fig. 10 and 12). Then it seems to be possible, that prolonged winter circulation was the reason for the significant decrease in sediment OM. It also is interesting, that such an effect was not significant for analyzed water strata (Fig. 16). This means, that rather the performed restoration procedures had a stronger influence on observed hydrochemical parameters, than prolonged winter circulation.

The very warm winter (2019/2020) in Poland was preceded by the warmest year in records (2019) in the last 30-years observation period between 1991–2020 (Tomczyk and Bednorz 2022). It is possible, that higher water temperature in this warm year induced the highest rates of organic matter decomposition in the bottom sediment of Mielenko Lake. The lower amounts of organic matter and two main nutrients (TN and TP), compared to the first year of research (2013) seem to confirm this supposition. Also, higher ammonium and phosphate concentrations were measured in the near-bottom and interstitial waters. Probably faster organic matter mineralization resulted in higher nutrient internal loading rates in 2019, which was the main reason for the highest annual phytoplankton biomass with an observed maximum (125.41 mg dm^{-3}) in the summer season. Scheffer (2004) and Abell et al. (2020) mention that in shallow eutrophic lakes, the turbid water state is maintained by high nutrient internal loading.

Conclusion

Our research seems to confirm the view that the lack of ice cover in the winter season can significantly affect the functioning of shallow temperate lakes, leading to increased mineralization of organic matter in sediments remaining in the active bottom zone and increasing P and N internal loading. This can lead to an increase in phytoplankton biomass and the consolidation of a turbid water state dominated by phytoplankton. The use of restoration methods that limit nutrients' internal loading can bring positive effects in such cases.

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Author contribution All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Renata Augustyniak-Tunowska, Jolanta Grochowska, Rafał Karczmarczyk, and Agnieszka Napiórkowska-Krzebietke, Miquel Lürling. The first draft of the manuscript was written by Renata Augustyniak-Tunowska and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Enquiries about data availability should be directed to the authors.

Declarations

Conflict of interest The authors declare no conflict of interest.

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