

Original Research

Changes in the Trophic Status of Three Mountain Lakes – Natural or Anthropogenic Process?

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Abstract

Three sediment cores have been studied from the Morskie Oko (MOK), Przedni Staw Polski (PSP), and Czarny Staw Gąsienicowy (CSG) lakes to examine the recent environmental history of the alpine lakes located in the Polish part of the Tatra Mountains (Carpathians). Changes in the total phosphorus concentration in the water over the past centuries were reconstructed based on diatom data (DI-TP), assuming that diatoms are good indicators of productivity in lakes. The results of the analysis showed significant alterations in the trophic status of the studied lakes over the past 50 years. Clear changes from oligotrophy to mesotrophy occurred in the lakes located close to year-round mountain huts on the shores of MOK and PSP. In contrast, DI-TP decreased in CSG, and the only symptom of higher productivity in the lake was an increase in total organic carbon.

Keywords: mountain lakes, eutrophication, diatoms, diatom-inferred TP, Tatra Mountains

Introduction

During the last millennium, the eutrophication of lakes has become widespread in many regions of the world. A transformation from an oligotrophic to a mesotrophic and later to a eutrophic lake is a natural, long-term process that can take hundreds to thousands of years. However, anthropogenic eutrophication may occur within a considerably shorter timeframe [1]. The major cause of lake eutrophication is an excess of nutrients, mainly phosphorus and nitrogen [2]. Anthropogenic sources of these nutrients include sewage, fertilizer runoff, soil erosion, animal waste, and industrial discharge [3]. Increased nutrient concentration in water can cause overstimulation of algae and plant growth, which in turn can use up dissolved oxygen as they decompose and block light to the deeper waters [4]. This phenomenon has occurred recently to a great extent in the lowland areas. Mountain areas are devoid of extensive industrial

infrastructure, but tourist development and increasing human population in the mountainous regions may result in a stronger human impact on mountainous ecosystems. However, lakes located in the same tourist region can be affected to different degrees by nutrient deposition. There is much we still do not know about the impact of tourism on mountain lakes. Many studies have focused on the impact of acid deposition on the status of mountain lakes, but the direct influence of tourists has been studied to a lesser extent. For instance, a strong tourism-induced pressure on lakes was detected in some mountainous regions of the Iberian Peninsula and the Swiss Alps [5-7]. These studies proved the important role of tourist-induced soil erosion and sewage input in changes in mountain lakes' trophic status.

The Tatra Mountains are a very popular tourist destination throughout the year. The most frequently visited lake in this area is Morskie Oko. Easy access to the lake and the opportunity to ride in a horse-drawn carriage causes the lake to be visited by over 2,000 tourists daily in summer [8]. Every year, approximately three million tourists visit

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the Polish Tatra National Park. Tourist activity is associated with direct or indirect interference with terrestrial and aquatic ecosystems. The impact of tourism on the alpine lakes is not limited to the introduction of live wastes to the water. Also contributing to the impact is the higher input of nutrients resulting from the increased rate of soil erosion around lakes [5]. Many scientists have studied human influences on the lakes in the Tatra Mountains. During the last few decades, these studies have mainly concerned anthropogenic acidification [9-14]. However, very few such studies have assessed the influence of tourism development on the eutrophication of mountain lakes [8, 15, 16]. In the case of oligotrophic lakes, minor inputs of nutrients may be enough to initiate changes in the lake ecosystems and move them toward mesotrophy [17]. One of the symptoms of an increasing trophic state is a change in the phytoplankton and zooplankton assemblages. Greater nutrient inputs limit the development of oligotrophic species and allow the expansion of mesotrophic and eutrophic taxa. According to the OECD Fixed Boundary Trophic Classification System [18] the mean phosphorus concentration in oligotrophic lakes varies between 4 and 10 $\mu\text{g}\cdot\text{L}^{-1}$, whereas in mesotrophic lakes, the concentration varies between 10 and 35 $\mu\text{g}\cdot\text{L}^{-1}$. Higher values of total phosphorus content are observed in eutrophic and hypereutrophic lakes.

The main aim of this study is to determine the human impact on the trophic state of alpine lakes during recent centuries. We analyzed these processes across different climatic epochs: Medieval Warm Period (MWP), Little Ice Age (LIA) and 20th century climate warming. We selected three lakes located in the Polish part of the Tatra Mountains: Morskie Oko (MOK), Przedni Staw Polski (PSP), and Czarny Staw Gąsienicowy (CSG), to identify natural or anthropogenic trophic state changes. Two of these lakes,

MOK and PSP, are located close to year-round mountain huts built in the early and mid-20th century, and the CSG was selected as a reference site. Changes in the trophic levels were inferred using subfossil diatoms (diatom-inferred TP) and the total organic carbon (TOC) concentration. Analyses of the biotic communities and reconstruction of the total phosphorus concentration from the lake sediments can help to determine the influence of the mountain huts exploitation on the trophic changes in lakes. We expected that shifts in the trophic status of the studied water bodies were caused mainly by human impact, e.g., tourism development and NO_x pollution, but that climate change also had an influence on the lakes' productivity.

Materials and Methods

Studied Sites

The lakes MOK, PSP, and CSG are located in post-glacial cirques in the Tatra Mountains of southern Poland (Fig. 1). The morphometric and chemical descriptions of the studied lakes are summarized in Table 1. The lakes are all situated on the type of catchment known as meadow-rocks, having 30 to 70% meadows and/or rocks [11, 13]; however, they are located in different valleys: MOK is in the Rybi Potok Valley, PSP is in the Pięć Stawów Polskich Valley, and CSG is in the Gąsienicowa Valley. The catchments of the studied lakes are composed of crystalline rocks (mainly granites) with quaternary glacial sediments and rock debris cones. The ice-cover period on the lakes lasts from November to May/July. The area around MOK is vegetated by the stone pine (*Pinus cembra*), and the areas around PSP and CSG by the dwarf pine (*Pinus mugo*).

Fig. 1. Location and bathymetric maps of the lakes Morskie Oko (A), Przedni Staw Polski (B), and Czarny Staw Gąsienicowy (C).

Table 1. Morphometric and chemical characterization of the studied lakes.

	MOK	PSP	CSG
Latitude	49°11'49"N	49°12'45"N	49°13'52"N
Longitude	20°04'14"E	20°02'58"E	20°01'05"E
Altitude (m a.s.l.)	1,395	1,668	1,624
Area (ha)	34.93	7.71	17.94
Catchment area (ha)	630	n.a.	205
Max depth (m)	50.8	34.6	51.0
Secchi depth (m)	12.0	n.a.	12.0
pH*	7.13	7.23	6.49
ANC (μmol/L)*	145.0	245.0	51.0
TP (μg/L)**	8.27	15.01	7.32
TON (μmol/L)*	9.2	10.8	5.6
Chlorophyll- <i>a</i> (μg/L)*	1.2	8.4	2.5

*After Kopáček et.al. [11]

**calculating according to the molybdate method

n.a. – data not available

MOK is the largest well-stratified lake in the Tatra Mountains (Table 1) with a native population of brown trout (*Salmo trutta* L. 1758). PSP is a relatively small lake located in the eastern part of the valley. CSG is the fourth deepest lake in the Tatras, and its catchment area is relatively small. PSP and CSG have been artificially stocked with fish [19, 20]. Fish were introduced to CSG in 1881, while PSP was stocked with trout in 1949, with main stocking in the 1960s and 1970s. CSG and PSP are located in the alpine zone above the tree-line ~1,550 m a.s.l., while MOK is located below the tree-line.

Coring and Dating of Sediment Sequences

Short cores of MOK (34 cm long), PSP (50 cm long), and CSG (35 cm long) sediments were collected using a Kajak-type gravity sediment corer at the central points of the lakes (Fig. 1). Cores with a diameter of 5 cm were obtained from the following depths: MOK-50 m, PSP-34 m, and CSG-50 m, and they were subsampled every 1 cm in the field. The sediments were macroscopically examined, and several terrestrial plant macrofossils (mainly dwarf pine leaves) were selected for radiocarbon dating. Sediment samples that were less than 150 years old were dated using the ^{210}Pb dating method in the Institute of Geological Sciences, P.A.S., in Warsaw, while the ages of the older sediments were determined using the radiocarbon method in the Radiocarbon Laboratory in Poznań with an accelerator mass spectrometer.

The ^{210}Pb activity of the sediments was determined indirectly via alpha spectrometry, which measured ^{210}Po activity [21]. A known amount of ^{208}Po was added to the sample as an internal yield tracer. Polonium was separated from the

sample using strong hydrochloric and nitric acid, deposited on silver disks [21] and measured using an alpha spectrometer. The topmost section of each core (to a depth of 11 cm in PSP and CSG and to a depth of 15 cm in MOK) was measured every 1 cm, and several additional measurements from deeper sections were performed for the supported ^{210}Pb calculations. The constant rate of the unsupported ^{210}Pb supply model (CRS) was used to calculate sediment age [22]. The age-depth function was calculated using the randomization method, and the curve was fitted using the LOESS procedure [23]. Then, the age-depth model was combined with radiocarbon dating. The radiocarbon dates were calibrated using Oxcal software version 4.10 [24], and the probability distributions (2σ) of these radiocarbon dates were plotted with the results of the ^{210}Pb -based age-depth model.

Sediment Analysis:

Diatoms, Isotopic Data: $\delta^{13}\text{C}$, $\delta^{15}\text{N}$

and Quantitative Analyses:

C/N Ratios and Total Organic Carbon (TOC)

The cores for the sediment analyses were subsampled every 2 cm. The sediments from 1 cm intervals were homogenized before subsampling. The density was determined by weighing a known volume of the sediment sample. The water content was calculated after drying at 105°C for 24 h.

The samples for diatom analysis were prepared according to the Battarbee method [25]. Approximately 1 cm³ of wet sediment samples were heated with 30% H_2O_2 until all organic matter was oxidized. Permanent slides were mounted with Naphrax® (RI = 1.75). At least 300 diatom valves were identified on each slide of randomly chosen transects using a biological microscope at 1000× magnification. The diatom taxonomy was largely after Krammer and Lange-Bertalot [26-29] and Lange-Bertalot and Metzeltin [30]. For the more recent nomenclature of diatoms, data from AlgaeBase (www.algaebase.org) were used. Stratigraphic diagrams were generated using POLPAL software [31]. The major diatom biozones were determined using the ZONE version 1.2 program [32].

For isotopic data analyses, the $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and quantitative analyses, the C/N ratios and the TOC concentration, the samples were treated with 5% HCl to remove carbonates and washed with distilled water. Next, the samples were dried at 105°C and ground in an agate mortar. The percentage of TOC was determined using a Flash EA 1112 elemental analyzer, and the stable isotope composition was measured with a Thermo MAT 253 mass spectrometer calibrated using an internal nicotinamide standard [33]. This analysis was performed in the Stable Isotope Laboratory of the Institute of Geological Sciences of the Polish Academy of Sciences in Warsaw.

Diatom-Inferred TP Reconstruction and Correspondence Analyses

Reconstructions of total phosphorus were conducted using the European Diatom Database (EDDI) and ERNIE

software, version 1.0 [34]. Diatom-inferred total phosphorus was calculated using the combined TP dataset [e.g., 35]. Only diatoms that were present at > 1% and occurred at an incidence greater than three per sample were used in the reconstruction. The reconstruction of TP was performed using the weighted averaging method with classical deshrinking because the reconstructed values lie toward the end of the gradient sampled by the training set [36]. The correlation coefficient (r^2) was 0.64, and the root mean square error of prediction (RMSEP) was 0.39 log-transformed TP. The modern analogue technique (MAT) was performed to determine the closest analogue, i.e., the minimum dissimilarity (minDC), between the fossil and modern samples in the calibration set. The fossil samples beyond a minDC value of 100–150 have no good analogues in the training set, which is based on the distribution of dissimilarities within the training samples [34]. Samples with no good analogues should be treated with caution, even if the majority of fossil taxa are present in the modern training set.

The species composition of the diatoms and its relationship to selected environmental variables were analyzed using the ordination methods of the Canoco software package [37]. Detrended correspondence analysis (detrending by segments) was applied to recognize the inter-set variability of diatom assemblages [38] and to detect the length of the gradient in every data set. Because the gradients were significantly long (>3.0 SD) and detected a modest to clear unimodal response of the species data along the gradient, we applied canonical correspondence analysis (CCA) to check the relationships between diatom species composition and the TOC, the C/N ratio, and the stable isotope composition of carbon and nitrogen. The significance of all variables and of the first and all canonical axes was tested using a Monte Carlo permutation test (9,999 unrestricted permutations). We also tested the correlation between the first canonical axis scores of the sample and DI-TP and between DI-TP and TOC using standard linear regression.

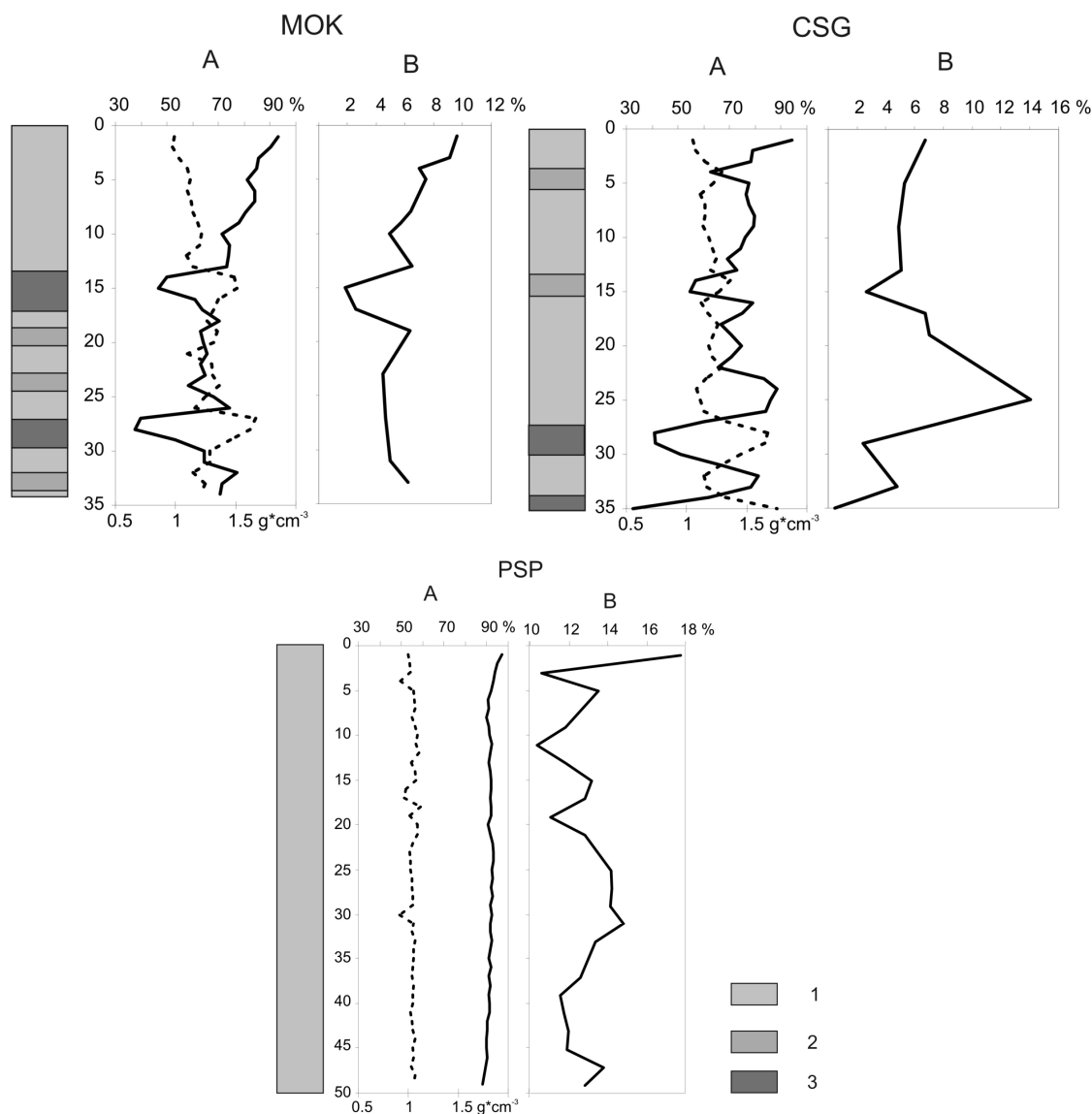


Fig. 2. Lithology of studied sediment sequences: A – water content (solid lines) and bulk density (dashed lines); B – total organic carbon. Key to lithology: 1 – fine detritus and silty gyttja, 2 – fine sand, 3 – coarse sand and gravel.

Results

Morskie Oko Lake (MOK)

Lithology and Chronology

The studied section of the sediment sequence was composed of dark green, silty gyttja (density 1.0-1.25 g·cm⁻³; water content 65-93%) with fine sand lamina (Fig. 2). This sequence was overlaid with two packages of coarse sand with micras (at 14-16 cm and 27-30 cm) and eroded granite grains (density 1.5-1.7 g·cm⁻³; water content 35-50%). The total organic carbon varied between 1.84% at a depth of 15 cm (ca. 1830 AD) and 9.60% at a depth of 1 cm (ca. 2010 AD).

The total specific ²¹⁰Pb activity ranged from 839±35 Bq·kg⁻¹ at 2 cm to 4.6±0.6 Bq·kg⁻¹ at 14 cm (Fig. 3). The calculated activity of the supported ²¹⁰Pb was 9.4±3.0 Bq·kg⁻¹, and the supported lead level was reached at a depth of 14 cm. An age-depth model based on ²¹⁰Pb dating was in

good agreement with radiocarbon dating (Table 2), and the combined model was consistent. The sedimentation rate was lowest at the 19-14 cm level.

Diatom Stratigraphy

Altogether, 146 diatom taxa belonging to 38 genera were identified (Fig. 4). The most common genera were *Achnanthes sensu lato* (s.l.) (20 taxa), *Cymbella* s.l. (14), *Eunotia* (13), *Navicula* s.l. (13), and *Fragilaria* s.l. (10). The core was divided into four diatom assemblage zones (DMOK 1-DMOK 4):

DMOK 1 (33-20 cm; ca. 1560-1710 AD)

This zone was dominated by planktonic *Fragilaria nanana* Lange-Bertalot and *Discostella pseudostelligera* (Hustedt) Houk & Klee. The frequencies of the benthic *Achnantheidium minutissimum* species group, *Psammothidium levanderii* (Hust.) Bukhtiyarova & Round, and *Denticula tenuis* Kützing were lower than 10%.

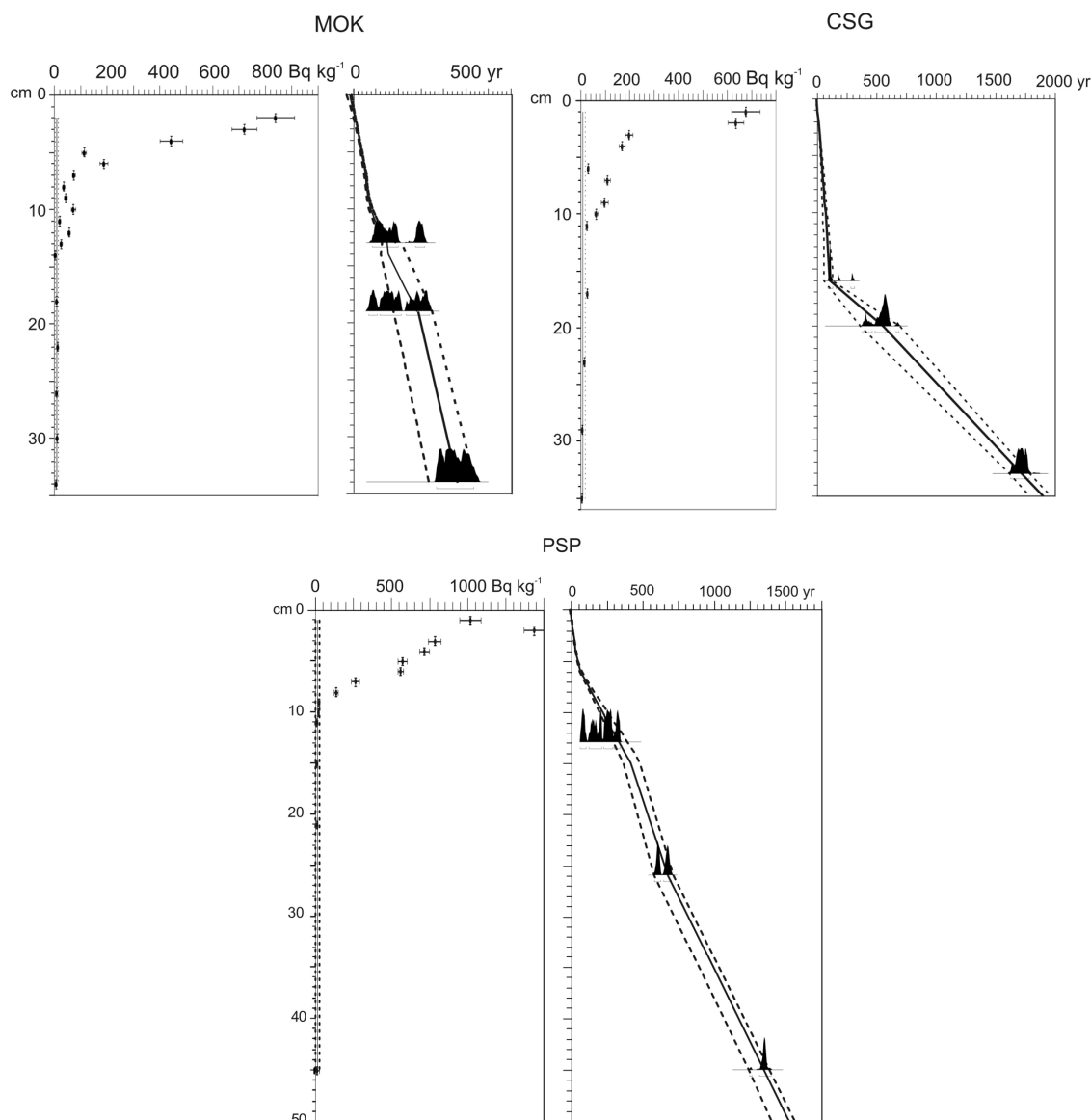


Fig. 3. Total specific activity of lead ²¹⁰Pb (A) and depth-age models (B) of studied sediment sequences. Age-depth functions are drawn with solid lines and model confidence ranges with dashed lines. Radiocarbon dates are reported as probability distribution spectra.

Table. 2. Summary of radiocarbon dating. The calibrated ranges were obtained using the IntCal09 calibration curve of Reimer et al. [72] and OxCal v 4.1.7 [24].

Sample name	Laboratory number	Depth in a profile	Radiocarbon date BP	Calibrated calendar date (95.4 % probability)	dated material
MOK 13	Poz-33196	13 cm	85±30BP	1688AD (25.6%) 1730AD	<i>Pinus cembra</i> leaf
				1809AD (69.8%) 1927AD	
MOK 19	Poz-33197	19 cm	130±30 BP	1675AD (37.9%) 1778AD	pine leaf
				1799AD (42.5%) 1894AD	
				1905AD (15.0%) 1942AD	
MOK 34	Poz-33198	34 cm	335±30 BP	1474AD (95.4%) 1641AD	pine leaf
PSP 13	Poz-36461	13 cm	150±30 BP	1667AD (16.3%) 1709AD	dwarf pine leaf
				1718AD (31.5%) 1784AD	
				1796AD (30.3%) 1890AD	
				1910AD (17.3%) 1951AD	
PSP 26	Poz-36462	26 cm	560±30 BP	1306AD (49.8%) 1363AD	dwarf pine leaf
				1385AD (45.6%) 1430AD	
PSP 45	Poz-36464	45 cm	1350±30 BP	636AD (87.7%) 715AD	<i>Carex</i> leaf
				744AD (7.7%) 768AD	
CSG 16	Poz-33178	16 cm	12±30 BP	1696AD (15.9%) 1726AD	dwarf pine leaf
				1814AD (11.1%) 1836AD	
				1847AD (0.8%) 1851AD	
				1877AD (67.7%) 1918AD	
CSG 20	Poz-33179	20 cm	450±60 BP	1324AD (2.6%) 1346AD	wood
				1393AD (75.3%) 1529AD	
				1552AD (17.5%) 1634AD	
CSG 33	Poz-33181	33 cm	1745±30 BP	227AD (95.4%) 389AD	dwarf pine leaf

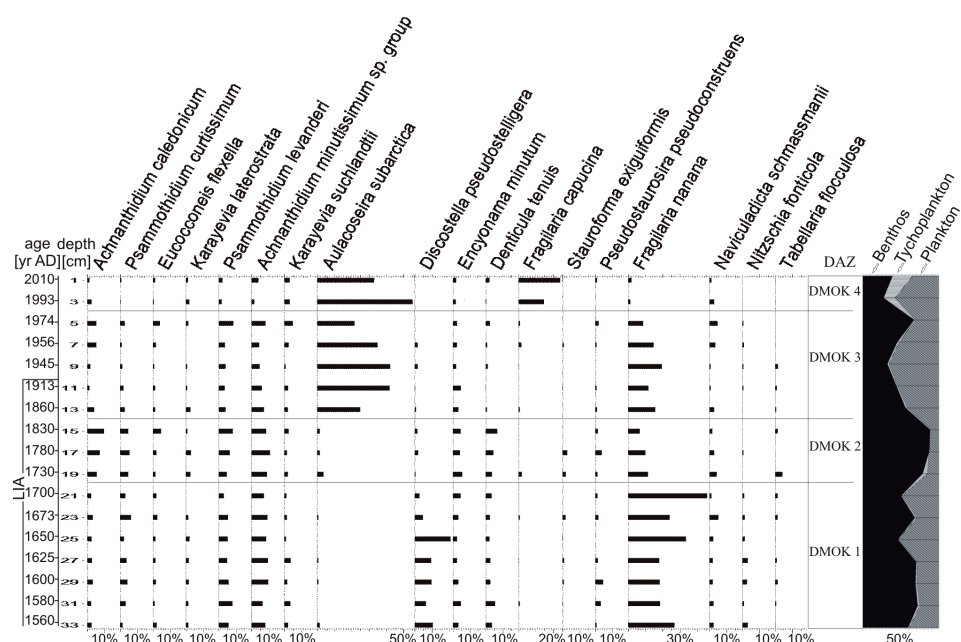


Fig. 4. Stratigraphy of the most abundant diatoms (species occurring at > 5%) of Morskie Oko Lake (MOK).

Table 3. Number of taxa (N), effective number of taxa (N2), and the sum of all taxa (Sum) for each fossil sample and distance to the closest modern analog (minDC) in the combined TP training set for samples from Morskie Oko (MOK), Przedni Staw (PSP), and Czarny Staw Gąsienicowy (CSG) lakes.

Sample	Data			Calibration set		
	N	N2	Sum	N	Sum	minDC
MOK						
1	38	5.47	100	35	99.10	100.0957
3	34	3.00	100	30	98.80	78.3167
5	43	10.71	100	39	98.80	104.9682
7	45	6.21	100	39	97.80	82.5437
9	43	4.45	100	37	97.80	77.0229
11	49	4.93	100	45	98.80	80.7133
13	52	9.21	100	44	96.00	100.9187
15	58	16.27	100	46	93.90	98.0780
17	50	15.63	100	41	95.00	105.8284
19	52	18.83	100	42	94.00	109.1322
21	45	4.40	100	37	95.00	80.0480
23	50	11.01	100	45	96.30	98.0532
25	36	5.72	100	31	97.70	80.8314
27	55	14.56	100	49	95.60	103.1347
29	47	13.42	100	43	96.80	101.5224
31	59	15.46	100	51	94.90	107.4910
33	50	9.47	100	44	97.10	90.1236
PSP						
1	16	2.74	100	15	99.10	56.7795
2	13	2.90	100	13	100.00	72.8963
3	18	3.35	100	17	99.50	77.5450
5	35	6.30	100	32	96.50	85.8064
7	41	15.25	100	37	79.20	107.4560
9	46	18.36	100	41	94.40	89.5321
11	39	12.25	100	37	98.00	66.5321
13	40	6.58	100	36	70.80	149.7253
15	37	6.46	100	34	68.90	148.4617
17	39	14.87	100	36	94.00	86.4693
19	32	10.86	100	28	95.80	75.0460
21	47	15.87	100	41	89.70	116.6314
23	40	10.51	100	36	97.00	121.8738
25	40	18.59	100	35	95.10	89.7739
27	38	13.09	100	33	97.40	110.6665
29	40	20.62	100	37	95.90	88.6720
31	42	22.16	100	39	96.30	99.6535
33	35	13.47	100	31	94.70	70.669
35	36	15.02	100	33	97.10	83.5363
37	38	11.01	100	34	96.60	88.1238

Table 3. Continued.

Sample	Data			Calibration set		
	N	N2	Sum	N	Sum	minDC
39	39	11.95	100	33	95.60	82.7226
41	40	11.11	100	33	94.50	86.5065
43	35	10.82	100	30	95.70	77.0847
45	39	13.43	100	36	97.00	75.6112
47	43	15.81	100	39	97.00	105.3716
49	33	9.16	100	30	98.40	85.9125
CSG						
1	58	11.10	100	48	90.80	128.5261
3	41	6.58	100	32	89.90	108.0496
5	37	3.06	100	31	97.00	94.1196
7	42	2.42	100	33	95.60	85.1472
9	34	2.24	100	28	95.20	88.4821
11	44	3.19	100	36	93.90	91.5767
13	57	16.73	100	46	84.60	132.3405
15	50	15.58	100	41	84.80	122.9981
17	41	3.20	100	34	92.90	90.5360
19	44	6.43	100	36	88.00	104.4829
21	43	6.95	100	35	90.70	105.9608
23	51	13.03	100	44	95.70	104.2030
25	46	14.47	100	39	87.30	128.8236
27	53	15.83	100	40	85.50	116.4359
29	52	20.83	100	42	82.20	93.633
31	52	18.33	100	45	82.30	108.1663
33	47	16.23	100	40	89.50	91.7629
35	49	19.38	100	38	84.10	96.188

DMOK 2 (20-14 cm; ca. 1710-1855 AD)

This zone is characterized by an increase in benthic taxa (*Achnanthisdium caledonicum* (Lange-Bertalot) Lange-Bertalot, *Denticula tenuis*). The diatoms that dominated the previous zone decreased in occurrence, especially *Fragilaria nanana* and *Discostella pseudostelligera*.

DMOK 3 (14-4 cm; ca. 1855-1985 AD)

Planktonic *Aulacoseira subarctica* (Müll.) Haworth was the dominant taxon in DAZ 3. An increase in *Fragilaria nanana* was observed, whereas the frequency of the benthic species decreased.

DMOK 4 (4-0 cm; ca. 1985-2010 AD)

The youngest sediments were dominated by *Aulacoseira subarctica* and tychoplanktonic *Fragilaria capucina* Desmazières. The frequency of *F. nanana* decreased.

Reconstruction of Diatom-Inferred Total Phosphorus (DI-TP)

Diatom-based reconstructions revealed that the highest TP concentration of 23 $\mu\text{g}\cdot\text{L}^{-1}$ was ca. 1993 AD (at 3 cm depth), while the lowest was ca. 1830 AD (6 $\mu\text{g}\cdot\text{L}^{-1}$ at 15 cm depth). The average value of DI-TP was approximately 11 $\mu\text{g}\cdot\text{L}^{-1}$. According to the MAT analysis, the minDC values varied between 77 and 108 (Table 3). From the 17 samples, nine of the fossil samples were outside a minDC range of 100-150 and have no good analogues in the modern training set (Fig. 5). However, fossil diatom flora are well represented in the modern training set: the species that occurred in both the fossil samples and the training set varied between 94 and 99% (Table 3).

The changes in the species composition of diatoms are explained by environmental variables. The first canonical

axis has a strong negative correlation with $\delta^{13}\text{C}$ values (Table 4, Fig. 6), and the second canonical axis is explained by the C/N ratio ($R^2=0.59$). Both canonical axes were statistically significant ($p\text{-value} < 0.001$). The reconstructed TP is correlated with the first canonical axis ($R^2=0.58$), and TP is weakly correlated with TOC (Fig. 7).

Przedni Staw Polski Lake (PSP)

Lithology and Chronology

The sediment core collected from PSP had a monotonous lithology and consisted of a dark brown fine detritus gyttja (density 1.0-1.1 g·cm⁻³; water content 88-97%). The TOC varied between 18% at 1 cm depth (ca. 2010 AD) and 11% at a depth of 3 cm (ca. 1990 AD).

The total specific activity of ²¹⁰Pb ranged from 1435±35 Bq·kg⁻¹ at 2 cm depth to 7.3±3.8 Bq·kg⁻¹ at 15 cm depth (Fig. 3). The calculated activity of the supported ²¹⁰Pb was 12.7±7.2 Bq·kg⁻¹, and the supported lead-210 level was reached at a depth of 11 cm.

Diatom Stratigraphy

A total of 111 species belonging to 33 genera were identified in PSP (Fig. 8). The most numerous genera were *Navicula* s.l. (23 taxa), *Achnanthes* s.l. (16), *Fragilaria* s.l. (11), and *Cymbella* s.l. (10). The lake sediments were divided into three zones (DPSP 1-DPSP 3), and the DPSP 2 zone was divided into three subzones.

DPSP 1 (49-32 cm; ca. 520-1125 AD)

Benthic diatoms, especially small forms of *Fragilaria* s.l. (such as *Staurosirella pinnata* (Ehr.) Williams & Round and *Pseudostaurosira pseudoconstruens* (Marciniak) Williams & Round) dominated this zone. In the lower part of the core, an increase in planktonic *Asterionella formosa* Hassall and *Fragilaria nanana* were observed.

Table 4. Correlation coefficients of environmental variable and the two first canonical axes of diatom assemblages.

	Axis1	Axis2	p-values
MOK			
$\delta^{13}\text{C}$	-0.91	-0.06	0.004
$\delta^{15}\text{N}$	-0.83	0.06	0.076
TOC	0.80	-0.01	0.202
C/N	-0.41	-0.59	0.050
PSP			
$\delta^{13}\text{C}$	-0.66	-0.63	0.005
$\delta^{15}\text{N}$	-0.91	0.08	<0.001
TOC	0.41	0.41	0.463
C/N	0.07	0.31	0.643
CSG			
$\delta^{13}\text{C}$	-0.54	-0.44	0.080
$\delta^{15}\text{N}$	0.49	0.01	0.364
TOC	-0.34	0.45	0.204
C/N	-0.40	0.39	0.437

Significant ($p \leq 0.05$) correlations between environmental variable and the species data are in bold.

DPSP 2 (32-6 cm; ca. 1125-1948 AD)

This zone consists of three subzones (2a, 2b and 2c). Subzone 2a (32-16 cm) was dominated by benthic/epiphytic *Pinnularia microstauron* (Ehr.) Cleve. The lower part of this subzone was characterized by an increase in the frequency of *Asterionella formosa*. The upper part of the subzone was dominated almost exclusively by the benthic taxa, e.g., *Staurosirella pinnata* and *Pseudostaurosira microstriata* (Marciniak) Flower.

Fig. 5. Diatom-inferred TP of Morskie Oko Lake (MOK), Przedni Staw Polski Lake (PSP), and Czarny Staw Gąsienicowy Lake (CSG).

Subzone 2b (16–12 cm) was dominated by *Naviculadicta digitulus* (Hust.) Lange-Bertalot & Metzeltin and *Sellaphora seminulum* (Grun.) Mann.

Subzone 2c (12–6 cm) was characterized by a decrease in the frequency of the taxa that dominated in the previous subzone. Similar to subzone 2b, the proportions of benthic to other diatoms were high.

DPSP 3 (6–0 cm; ca. 1948–2010 AD)

The diatom assemblages in this interval were completely different from the rest of the core. The abundance of planktonic taxa such as *Discostella pseudostelligera*, *Fragilaria capucina*, and *F. nanana* increased significantly in this zone. Additionally, the frequency of benthic diatoms decreased, especially in the uppermost samples.

Reconstruction of Diatom-Inferred Total Phosphorus (DI-TP)

The reconstructions revealed that TP reached its maximum concentration ca. AD 1677 (35 $\mu\text{g}\cdot\text{L}^{-1}$ at 13 cm depth)

and a minimum concentration of 11 $\mu\text{g}\cdot\text{L}^{-1}$ (at 9 cm depth) ca. AD 1831. As a result of the MAT analysis, only eight of the 26 fossil samples had good analogues in the modern training set (Fig. 5). The values of minDC ranged between 57 and 150, and the lowest occurrence of fossil diatoms in the calibration data sets was 69% (Table 4).

The Monte Carlo permutation test indicated that both canonical axes were statistically significant ($p\text{-value} < 0.001$). The CCA results showed good negative correlation of both canonical axes to the carbon isotopic composition and a strong relationship of the first canonical axis to the $\delta^{15}\text{N}$ values. The DI-TP has no correlation with the first canonical axis, and TP is not correlated with TOC (Fig. 7).

Czarny Staw Gąsienicowy Lake (CSG)

Lithology and Chronology

The CSG core was composed of dark green, silty gyttja (density 1.05–1.4 $\text{g}\cdot\text{cm}^{-3}$; water content 55–95%) with a lamina of fine sand (Fig. 2). This sequence was overlaid with two layers of coarse sand with micas (at depths of 27–30 cm and 35 cm) and eroded granite grains (density 1.45–1.75 $\text{g}\cdot\text{cm}^{-3}$; water content 32–50%). The highest concentration of TOC was 14% at a depth of 25 cm (ca. 1010 AD), and the lowest value was below 1% at a depth of 35 cm (ca. 120 AD).

The total specific activity of ^{210}Pb ranged from 677 ± 29 $\text{Bq}\cdot\text{kg}^{-1}$ at the 1 cm level to 5.0 ± 0.3 $\text{Bq}\cdot\text{kg}^{-1}$ at the 35 cm level (Fig. 3). The calculated mean activity of supported ^{210}Pb was 8.5 ± 4.7 $\text{Bq}\cdot\text{kg}^{-1}$, and the supported lead level was reached at the 20 cm level.

The ^{210}Pb -based age-depth model was confirmed by the radiocarbon date (Table 2) of a plant macrofossil from a depth of 16 cm. The radiocarbon dating of macrofossils from the deeper part of the core suggests a significantly lower deposition rate in the lower section. This difference in ages may be the result of hiatuses in the lower section of the sequence, documented in the sediments by layers of fine and coarse sands (e.g., at the depth of 17 cm).

Diatom Stratigraphy

In total, 127 diatom species belonging to 40 genera were identified in the core (Fig. 9). The most abundant genera were *Achnanthes* s.l. (17 taxa), *Eunotia* (15), *Fragilaria* s.l. (11), *Navicula* s.l. (10), and *Cymbella* s.l. (8). The sediments were divided into four diatom assemblage zones (DCSG 1–DCSG 4):

DCSG 1 (35–24 cm; ca. 120–1105 AD)

This zone was characterized by an unchanging species composition. Benthic and tychoplanktonic species reached their maximum occurrence in this part of the core. The most frequently occurring species were *Aulacoseira lirata* (Ehr.) Ross, *Pseudostaurosira brevistriata* (Grun.) Williams & Round, *Karayevia suchlandtii* (Hust.) Bukhtiyarova, *Naviculadicta schmassmanii* (Hust.) Werum & Lange-Bertalot, and *Denticula tenuis*.

Fig. 6. Canonical correspondence analysis plots for Morskie Oko Lake (MOK) and Przedni Staw Polski (PSP). Environmental variables ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, total organic carbon (TOC), C/N ratio) are expressed as vectors, dominant diatom taxa as solid circles, and dated samples as empty circles.

DCSG 2 (24-14 cm; ca. 1105-1915 AD)

A significant increase in *Fragilaria nanana* was found; however, at the top of this zone its frequency decreased by several percentages. In this zone, *Discostella pseudostelligera* occurred in only one sample at a depth of 23 cm, where it reached a frequency of 6%.

DCSG 3 (14-4 cm; ca. 1915-1986 AD)

This zone is characterized by the reoccurrence of *Fragilaria nanana*. This species reached its maximum frequency in the core (>65%). An increased abundance of benthic and tychoplanktonic diatoms was observed in the lower part of the zone.

DCSG 4 (4-0 cm; ca. 1986-2010 AD)

Benthic and tychoplanktonic species, such as *Aulacoseira alpigena* (Grun.) Krammer, *Psammothidium curtissimum* (Carter) Aboal, and *P. marginulatum* (Grun.) Bukhtiyarova & Round, increased significantly in this zone, while *F. nanana* decreased (from 35% to 18%).

Reconstruction of Diatom-Inferred Total Phosphorus (DI-TP)

The total phosphorus concentration ranged from 11 $\mu\text{g}\cdot\text{L}^{-1}$ at a depth of 33 cm to 5 $\mu\text{g}\cdot\text{L}^{-1}$ at a depth of 1 cm, and the average concentration was $\sim 8 \mu\text{g}\cdot\text{L}^{-1}$ (Fig. 5). The max-

Fig. 7. Correlation (linear regression) between first canonical axis scores and diatom-inferred TP and between diatom-inferred TP and TOC.

imum and minimum values of DI-TP occurred at approximately 300 AD and 2010 AD. In CSG, the minDC values varied between 85 and 132. Among 18 fossil samples, a good fit to the modern training set was observed in 10 samples (Fig. 5). In the modern calibration set, the lowest value of fossil taxa was 82% (Table 4).

According to the MC permutation test, both canonical axes were statistically insignificant (p -value = 0.244), and any environmental variable was correlated with the ordination axes. Moreover, DI-TP had a weak and negative correlation to the TOC values (Fig. 7).

Discussion

Evaluation of Diatom-Inferred TP Reconstruction

Diatoms are commonly used in quantitative reconstructions of past environmental variables, such as the pH, salinity, or productivity of lakes [39]. The tools used to reconstruct these factors include the modern diatom calibration sets, for example, available in the European Diatom Database (EDDI). However, no modern data set for the High Tatra Mountains exists, so we used the combined TP data to reconstruct total phosphorus for the studied lakes. We tested several databases from the EDDI and obtained the most reliable results for the combined TP data set. This data set was identified as possessing the highest number of matching analogue diatom taxa in the fossil assemblages using the modern analogue technique (MAT).

The diatom-inferred TP values may be overestimated to some extent, especially in MOK and PSP, because the modern diatom database used for the reconstruction contains

lakes with a long total phosphorus gradient. Nevertheless, an important issue is the trend of TP changes and the time of these alterations over the last millennium. This overestimation is also a result of the dominance of diatoms with high TP optima [40]. In the sediments of PSP during the main enrichment period, the frequency of *Discostella pseudostelligera* exceeded 50% in the youngest diatom assemblage. In the modern training set used for TP reconstruction, *D. pseudostelligera* occurs mostly in lakes with relatively high TP concentrations. In the sediments of MOK, an increase in the abundance of *Aulacoseira subarctica* and *Fragilaria capucina*, which can tolerate mesotrophic to eutrophic conditions, indicates higher nutrient levels [41]. However, a few single measurements of TP in the water column from MOK (Table 1), conducted in the 1990s and in 2004, indicate a lower TP concentration [11, 12, 13], which contradicts the DI-TP reconstruction results. The samples studied by Kopáček et al. [11, 12] and Stuchlík et al. [13] were taken in September because the lake water chemistry is more stable at that time than in the spring-summer period. Differences between the diatom-inferred TP and the measured TP values are noted in many studies [e.g., 42, 43, 40], probably because of the model and calibration-set properties and/or the high variability of TP content during the season. Moreover, the values of DI-TP reflect the average total phosphorus content in the sediments accumulated during one or even a few years and recorded in a single sample. The total phosphorus concentration is related to the degree and timing of the onset of thermal stratification. Therefore, some measurements of TP may not reflect the exact season and habitat for particular diatoms [44]. For example, *Aulacoseira subarctica* blooms in northern temperate and boreal lakes during the cold early spring, when

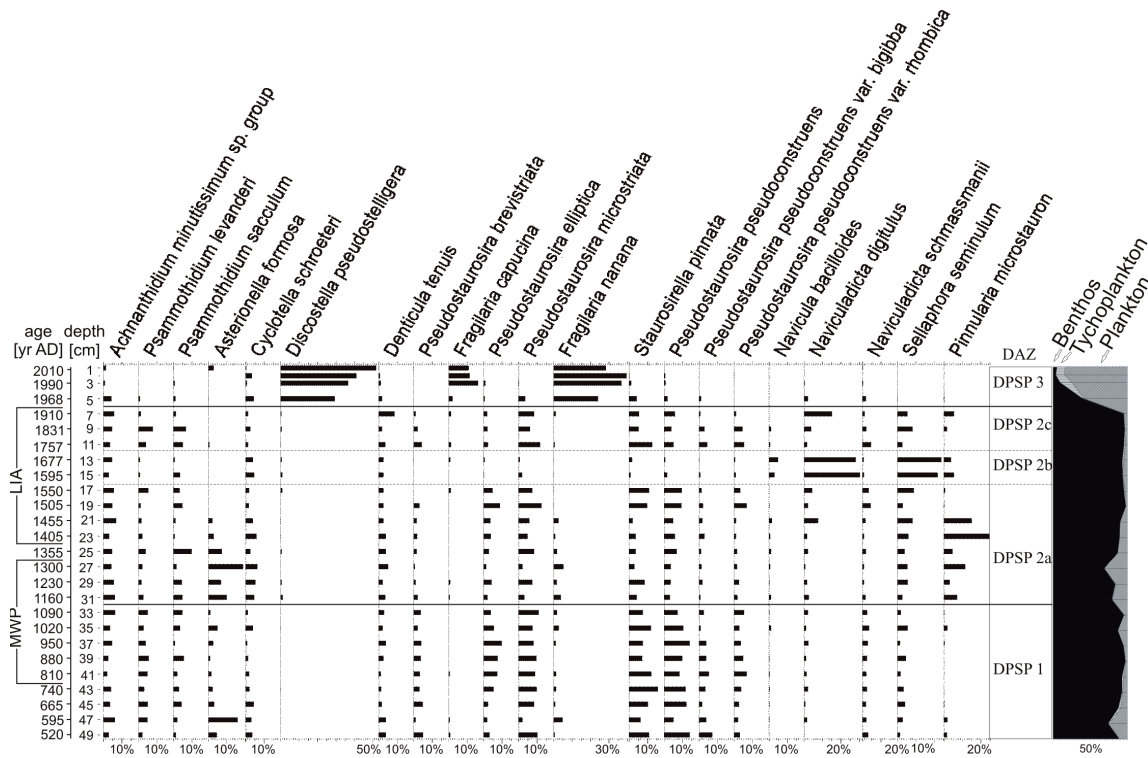


Fig. 8. Stratigraphy of the most abundant diatoms (species occurring at > 5%) of Przedni Staw Polski Lake (PSP).

low light becomes available for photosynthesis. This meso-eutrophic planktonic diatom marks the beginning of nutrient enrichment in oligotrophic ecosystems [45–47]. For these reasons, a perfect correspondence between the diatom community and total phosphorus concentration may be impossible [40]. Finally, reconstructed changes in DI-TP can in fact reflect changes in other nutrient concentrations, e.g., nitrogen, that cause significant changes in diatom species composition but are not correlated with changes of the TP concentration in water.

The results of the MAT analysis (minDC) indicate that there are several periods of the studied cores that have no good modern analogues (Fig. 5). The lack of close fit to the modern training set could be an effect of the abundance of a higher number of rare taxa in the dataset or/and an increase in the occurrence of the diatoms in the Tatra lakes, which were not common in the modern training set. However, the majority of taxa in the fossil samples are present in the modern calibration set. The best similarity between the fossil and modern training set is observed in MOK (Table 3).

We also used the TOC values as independent indicators reflecting the trophic state of the lakes to verify the reliability of DI-TP (Fig. 7). TOC was used as a good indicator of organic matter content and a tool to determine biomass production [48]. Linear regression coefficients were calculated to evaluate the relationship between DI-TP and TOC. A weak positive correlation was detected only in MOK, and there was no correlation in PSP. We even found a negative relationship in CSG, but it was not significant. The generally poor correlation between these two factors reflects the reduced availability of a major part of TOC to phytoplankton. Organic matter is not only produced within the lake, e.g., by algae and macrophytes; another important source of organic matter could be vascular plants, which can enter the lakes from the watershed [48]. The results of the C/N ratio indicate that the sources of the organic matter in the studied lakes were phytoplankton with a small admixture of terrestrial plant parts [33]. Organic matter with a large admixture of vascular plants usually has C/N ratios of 20 and greater [49]. These parts of the organic carbon source are weakly used by diatoms, as the decomposition rate of macroremains is relatively low in cold alpine lakes.

TP Evolution of Studied Lakes

In the sediments of MOK, two climatic periods are recorded: the Little Ice Age and 20th century climate warming. During the LIA, benthic diatoms were the dominant species in the lake. However, some planktonic taxa, such as *Fragilaria nanana* and *Discostella pseudostelligera*, were also present during that period (DMOK 1 zone). Among larger forms of planktonic *Fragilaria* spp., *F. nanana* is a taxon that can tolerate a relatively long duration of ice cover and low mean July water temperatures [50]. The occurrence of *Discostella pseudostelligera* indicates a relatively high trophic level [51, 52], but DI-TP was relatively low and stable and oscillated around 10 $\mu\text{g}\cdot\text{L}^{-1}$. The highest frequency of littoral/benthic diatoms was found between ca. 1710 and

1855 AD (DMOK 2 zone). The abundance of planktonic diatoms was small, which may reflect a deterioration of environmental conditions. Additionally, DI-TP and the clear decline in TOC point to a lower concentration of nutrients. The increase in benthic taxa may indicate lower availability of open water habitat or lower water turbulence [53]. After that, up to ca. 1860 AD, a larger frequency of high-energy rapid mass movements was described in the catchment of MOK [54, 55].

Reconstructions of the TP concentration revealed that the lake had an oligotrophic character almost to the end of the LIA; at this time, the value of DI-TP was still $\sim 10 \mu\text{g}\cdot\text{L}^{-1}$. A significant change in the diatom community and an increase in DI-TP have been characteristic of this lake since 1860 AD (DMOK 3 zone). From that time until the present, an increase in the abundance of planktonic *Aulacosiera subarctica* was observed, which indicates an increase of the trophic state of the lake. *A. subarctica* is common in circumneutral, mesotrophic to eutrophic lakes, and requires water turbulence to keep it in suspension; however, the TP optimum of *A. subarctica* is lower than the typical meso-eutrophic diatoms such as *Asterionella formosa*, which is an indicator of eutrophy. The occurrence of *A. subarctica* indicates mesotrophic conditions and changes in the growing season, i.e., longer ice-free periods [56, 57]. In the post-LIA period, a gradual increase in DI-TP concentration was observed, and the TOC content also increased, which indicates higher lake productivity. A decrease in DI-TP values took place between ca. 1956 and 1993 AD (Fig. 5). This decline coincided with the foundation of the Tatra National Park and the reduction of cattle grazing in the lake's catchment area.

After ca. 1993 AD, the reconstructed TP and TOC concentrations in the sediments increased. In the youngest sediments of MOK, the values of DI-TP were $\sim 20 \mu\text{g}\cdot\text{L}^{-1}$, which indicates the transformation into a mesotrophic lake. The two youngest samples are clearly separated along ordination axis 1 in the CCA diagram (Fig. 6). This axis is well explained by changes in $\delta^{13}\text{C}$ (Table 4), which were previously interpreted as a result of increasing pressure from intensive tourism [33]. Another factor, indirectly impacting phytoplankton of MOK could be the tree line position during the 20th century. Tree line altitude increased at this time as a result of higher temperatures after the end of the Little Ice Age. MOK is the only one of the studied lake located below present timberline. Indirect indicator of tree line position (and consequently lake's catchment area covered by forest) is C/N ratio recorded in the sediments. The changes in the diatom community are correlated with C/N ratio only in MOK (Table 4, Fig. 6). The lowest C/N values in the past-1993 samples can therefore be interpreted as a result of lower input of terrestrial plant remains to the lake. This can be a consequence of forest area spreading during the last few decades and lower erosion in the lake's catchment.

The sediment core of PSP contains a longer time record than MOK, and three global climatic epochs – the Medieval Warm Period (MWP), LIA, and 20th century climate warming – may be distinguished. Benthic diatoms dominated

between 520 and 1948 AD. The DPSP 1 and DPSP 2a zones (ca. 520–1570 AD) were characterized by the occurrence of small alkaliphilous *Fragilaria* s.l. During this time, eutrophic *Asterionella formosa* reached its highest frequency in the core. The trophic level in PSP was relatively stable until 1550 AD; the average value of DI-TP was approximately $15 \mu\text{g}\cdot\text{L}^{-1}$, indicating the slightly mesotrophic character of the lake. A progressive increase in DI-TP occurred between ca. 1550 and 1677 AD (DPSP 2b zone). The estimated value of DI-TP slightly exceeded $35 \mu\text{g}\cdot\text{L}^{-1}$, which indicates the meso-eutrophic state of the lake. During that time, the diatom community of PSP was dominated by benthic *Sellaphora seminulum* (often found in eutrophic and organically polluted water) and *Naviculadicta digitulus*. The last species also live in an aerial environment, i.e., it reaches an ecological optimum in the boundary between air and water [58].

The high frequency of the pseudaeerial taxa suggests a period of intense erosion and input of detrital material from the catchment to the lake sediments [59, 60]. During the Little Ice Age in the Tatra Mountains, extreme geological and climatic events occurred, such as an increase in mass movements, catastrophic floods, continuous precipitation, debris flows, and earthquakes [55]. Probably, as a result of these events, the lake received a greater load of nutrients from the surrounding watershed.

Additionally, for many years, the Pięć Stawów Polskich Valley was a cattle grazing site. Intensive grazing pressure has contributed to lowering the upper tree-line in the Tatra Mountains. The huge number of grazing sheep, the hooves of which caused destruction of the upper layer of soil and vegetation, accelerated an increase in erosion and the formation of landslides. Grazing was limited in 1953 and totally prohibited in 1968. Summer cattle grazing had a negative effect on the water quality in the lakes. Organic pollution such as cattle manure flowing into the lake, causing an increase in nitrogen and phosphorus concentrations. Consequently, the grazing pressure caused the eutrophication of naturally oligotrophic mountain lakes [61]. Changes of the tree-line are caused not only by human impact but also by natural factors, i.e., climate change. Historical data indicate that significant changes in timberline altitude took place at the end of the Little Ice Age as a result of temperature and moisture alterations. Despite an increase in total phosphorus, a greater frequency of planktonic diatoms that could tolerate high nutrient concentration was not observed during that time in PSP. Presumably, the low temperature was a factor limiting the expansion of the planktonic species. Following this period, the value of total phosphorus declined to ca. $12 \mu\text{g}\cdot\text{L}^{-1}$ (DPSP 2c zone); however, it was a relatively ephemeral shift (ca. 70 years), and at the end of the LIA period, the concentration of DI-TP increased again. Abrupt changes in the diatom assemblage structure were observed in the early 1970s. During this time, the main stocking of brown and brook trout took place in PSP. The introduction of fish can cause changes in the food web structure by disrupting nutrient cycles. Fish grazing pressure on large forms of zooplankton contributed to the growth of primary production in the lake [62]. Planktonic

diatoms preferring mesotrophic and/or eutrophic waters, such as *Fragilaria capucina*, *F. nanana*, and *Discostella pseudostelligera*, replaced the benthic taxa. From that time to the present, the average value of DI-TP was $\sim 22 \mu\text{g}\cdot\text{L}^{-1}$, which indicates mesotrophic conditions. The DI-TP values correspond to the measurements of TP made by Kopáček et al. [11] and indicate the lake's mesotrophic state. The high abundance of planktonic diatoms in the recent sediments of PSP indicates a longer growing season and/or nutrient enrichment. An increase in the primary productivity of the lake was confirmed by an increased TOC content of up to 17% in the youngest sediments of PSP. The youngest samples are very clearly separated from the rest on the ordination diagram along ordination axis 1 (Fig. 6). These samples indicated a clear decrease in $\delta^{15}\text{N}$ values, identified as a strong input of NO_x pollution to the lake [33]. This input may be another factor inducing the recent eutrophication of the lake.

In the CSG sediments it is possible to discern the following climatic periods: MWP, LIA, and 20th century climate warming. In the time preceding the MWP, the diatom flora mainly consisted of benthic taxa. However, some planktonic and tychoplanktonic diatoms were noted as well. The reconstruction of the TP indicates a decrease in the trophic level of the lake from slightly mesotrophic to oligotrophic. During the MWP, changes in the diatom community were not significant. The frequency of benthic taxa decreased during that time compared to the pre-MWP period. However, the occurrence of tychoplanktonic *Aulacoseira lirata* increased. This taxon is heavily silicified, prefers well-stratified lakes, and requires water turbulence to remain in the water column, indicating a high water level [63–65]. The climate during the MWP was relatively mild, with similar temperatures to the present [66]. The improving climatic conditions caused longer growing seasons, which resulted in an increase in lake productivity. The content of the TOC in the sediments of CSG reached a maximum value in the core during this time (Fig. 2). Usually, in arctic and alpine lakes, warmer temperatures contribute to plankton development, which is related to a shorter ice period and higher primary production [e.g., 67, 68]. In the sediments of CSG, a progressive increase in planktonic taxa abundance was observed (the upper part of DCSG 1 and the lower part of DCSG 2 zones). Climate changes throughout the LIA did not hinder the growth of plankton. The lack of glaciers in the Tatra Mountains during the LIA [69] and the high water level probably enabled the development of planktonic diatoms. As in MOK, the dominant species was *Fragilaria nanana* (DCSG 2 zone). The reconstruction of TP demonstrated the oligotrophic character of the lake. At the end of the LIA, the frequency of the benthic diatom flora increased. Significant shifts in the diatom assemblage structure were observed during the 20th century. These changes are almost certainly caused by climate warming after the LIA. During this period, the abundance of planktonic diatoms was the highest in the last 1900 years. The planktonic *Fragilaria nanana* was the dominant species (Fig. 9), similar to the sediments of Zielony Staw Gąsienicowy in the Tatra Mountains [14]. At the beginning

of the post-LIA period, an increase in diatom-inferred TP was recorded. The values of TP slightly exceeded $10 \mu\text{g}\cdot\text{L}^{-1}$, indicating oligo-mesotrophic conditions. Since ca. 1970 AD, the CSG changed to a typical oligotrophic lake, which was marked by a decline in DI-TP (Fig. 5). The measurements of Kopáček et al. [11, 12] also indicate the oligotrophic character of the lake.

An increase in DI-TP during the last century may also be an effect of eutrophication-like response of the plankton community to climate warming. The process of rise in zooplankton density was described from deep and large Lago Maggiore (N. Italy) [70]. However, eutrophication during the 20th century was observed only in some of the Tatra lakes. Therefore, other local conditions determined an increase in primary productivity.

In addition to natural environmental factors, some human-induced processes have also influenced environmental conditions in the studied lakes. Year-round tourist mountain huts are located close to MOK and PSP. The first shelters located at MOK were built in 1874 and 1876, although after a few years they were destroyed by fire. The current mountain hut at MOK has been active since 1907 and at PSP since 1953. The wastewater from the huts may change the trophic level of the lakes. As a result of the rise in nitrogen and phosphate compounds, especially during summer, an increase in trophic state was noted in these lakes [8, 16]. Since the construction of the sewage-treatment plant in the Morskie Oko mountain hut in 1992, the TP concentration decreased (Fig. 5). Because only two samples were analyzed encompassing the last 17 years, it is difficult to precisely determine the changes in the nutrient levels and the influence of the sewage-treatment plant on the trophic status of the lake. More detailed biological and chemical studies and water quality monitoring are recommended to determine if the construction of the sewage treatment plant significantly improves the lake's water quality.

The construction of the biological wastewater treatment plant in the mountain hut near PSP began in March 2010. Hopefully, this plant will also improve the conditions of the lake. Because good management of aquatic ecosystems requires knowledge of the timing and extent of environmental change in the lakes [71], this study should be helpful to environmental managers in Tatra Mountain National Park. The results of these analyses will complement the existing knowledge of the Tatra lakes and could be useful for the future protection of the lakes' ecosystems. Estimating the rate and amplitude of the changes in the lakes in the past and their current status can help to select lakes for special management.

Conclusions

1. Diatom-inferred TP reconstruction can be a reliable tool to study past trophic changes in alpine lakes. However, the reliability of these reconstructions should always be checked and verified by independent indicators of trophic state or productivity, e.g., TOC, stable isotope composition, and nutrient concentration.
2. This study revealed that the Tatra Mountain lakes experienced a rise in productivity during the 20th century. This rise was most likely due to the warmer temperatures after the Little Ice Age, which caused a decrease in ice cover length. This period involved a longer growing season, higher primary production and the increased availability of nutrients. Another important factor that altered the eutrophication process was the input of nitrogen from airborne NO_x pollution.
3. Alterations of trophic status, i.e., changes from oligotrophy towards mesotrophy, were clearly observed in the lakes located closer to the year-round mountain huts of MOK and PSP.

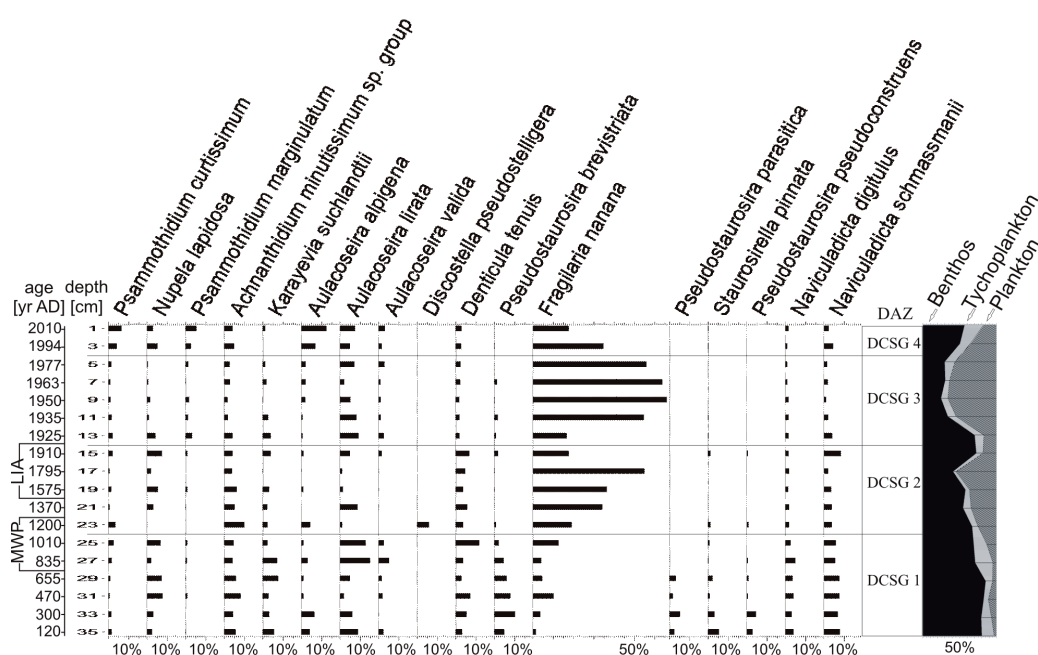


Fig. 9. Stratigraphy of the most abundant diatoms (species occurring at > 5%) of Czarny Staw Gąsienicowy (CSG).

4. No symptoms of significant eutrophication were found in the lake located the greatest distance from the shelters, i.e., in CSG. The content of the total phosphorus in this lake indicates an oligotrophic level for the post-LIA period. A similar trend in DI-TP was observed in other nearby lakes, such as Zielony Staw Gąsienicowy and Smreczyński Staw. Near these lakes, only hiking trials were marked. This result suggests that the lakes situated closest to the mountain huts are more affected by eutrophication.

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