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TOWARDS A QUANTITATIVE RECONSTRUCTION OF LAKE TROPHIC STATE IN TEMPERATE LAKES USING SUBFOSSIL CLADOCERA AND DIATOMS: COMPOSITION OF A TRAINING SET FROM NE POLAND

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Abstract

We present a training set, the database involving physical-chemical water parameters together with the subfossil Cladocera and diatoms community composition in the surface sediments of 64 postglacial lakes in NE Poland sampled along a wide trophic gradient (from oligo- to highly eutrophic). The most important water parameters measured in water were chlorophyll-*a*, electrical conductivity (EC) and oxygen concentration. In addition, total phosphorus (TP) and Secchi depth (SD) were determined for the surface water layer. The data collected will be used to calculate a transfer-function for quantitative reconstruction of trophic state in freshwater temperate lakes.

Key words

Lake training-set • water properties • summer vertical profiles • subfossil Cladocera • subfossil diatoms

Introduction

Lakes are important components of postglacial landscapes, sensitively reacting to environmental changes from local to global scale. Lake catchment features such as land cover and land use have a profound impact on the amount of nutrients reaching lake water and therefore they are very influential in terms of lake trophic status. The global climate changes also play a great role in shaping the habitats for water organisms as well as physical and chemical processes in lakes. The information on the current and past states of the lake ecosystem is preserved in lake sediments. By using a plethora of analytical methods including paleoecology, geochemistry, stable isotopes etc. paleolimnologists acquire this information and translate it into reconstructions of past environments on different time scales. In Central and Eastern European Lowlands lake bottom sediments have been accumulating since the termination of the last glaciation and consequently sediment cores from the deepest parts of lake basins often contain a high-resolution record of environmental changes since the fall of the last glaciation (Ralska-Jasiewiczowa et al., 1998; Lauterbach et al., 2011; Apolinarska et al., 2012; Zawiska et al., 2018).

The remains of planktonic organisms such as Cladocera and diatoms are known for being reliable paleoecological bioindicators (Battarbee et al., 2001; Korhola & Rautio, 2001). They respond sensitively to different environmental parameters such as pH, salinity, trophic state, water depth etc. and are very common in the sediments. The classical way of interpreting results of paleolimnological analysis is based on indicative species as well as a full assessment of the species composition of the entire subfossil communities (Korhola & Rautio, 2001) to perform qualitative reconstructions of the past environments. However, in order to get quantitative information on past environmental changes from the species composition preserved in the sediment cores, it is necessary to find relationships between environmental factors and the population composition. This approach has been successfully applied in paleolimnology during the last decades (Chalie & Gasse, 2002; Lamentowicz et al., 2009; Larocque-Tobler et al., 2015; Zawiska et al., 2015; Rzodkiewicz, 2018). Calculating a transfer function requires a good quality training set, consisting of lakes covering a wide range of values of parameters that will be reconstructed from the sediment cores. Such a training set act as a database involving in-situ and/or laboratory measurements of present-day environmental parameters and the composition of corresponding local biocenoses (Juggins & Telford, 2012).

There are few existing training-sets for Central and Eastern Europe for the diatoms (Sienkiewicz & Gąsiorowski, 2017; Witak et al., 2017; Rzodkiewicz, 2018; Sienkiewicz et al., 2021) and Chironomidae (Kotrys et al., 2020). However, so far there is no Cladocera-based training set from temperate latitudes. The existing ones were created in the regions with different climatic and geological conditions as well as vegetation and land-use changes, which made it unsuitable for paleoenvironmental reconstructions in temperate European latitudes (Brodersen et al., 1998; Lotter et al., 1998; Chen et al., 2010; Davidson et al., 2010; Nevalainen et al., 2013). In Poland the first attempt to bind subfossil Cladocera composition with environmental parameters was made for the group of dystrophic lakes in the Wigierski National Park (Zawisza et al., 2016). The ongoing research is centered on creating a Cladocera-based transfer function for reconstructing trophic state in freshwater temperate lakes. The first step was to built a training set for the above application. **The current paper aim is to provide the information on the composition and structure of this training set**. The training set encompasses a hydrochemical and ecological (primarily diatom and Cladocera composition) data from a number of lakes throughout the NE part of Poland. Lakes involved in the database represent a wide range of trophic status (from oligo- to highly eutrophic) which makes the dataset representative for the temperate lakes as a whole. The eutrophication processes in lakes in northeastern Poland are climate- and human-induced (Marszelewski, 2005) and it is important to determine the reference conditions to provide scientific advice for restoration programs applied to these ecosystems (Bennion et al., 2011; Luoto et al., 2013).

Study area

This study involves 64 lakes distributed over the area of around 30,000 km^2, located in NE Poland and at the transition between Mid and East European Plains. The lakes are located

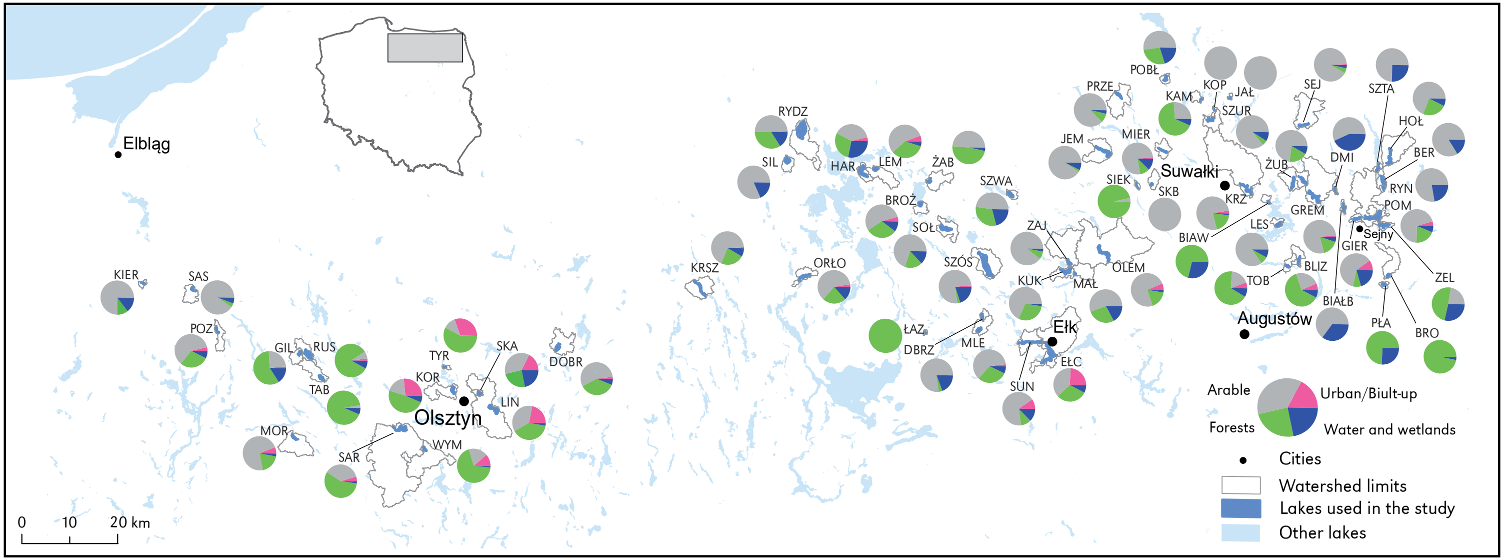


Figure 1. Study site location map with investigated lakes: BER – Berżnik, BIAB – Białe k. Białogóry, BIAW – Białe Wigierskie, BLIZ – Blizenko, BRO –Brożane, BROŻ – Brożówka, DŁUG – Długie Krasnopolskie, DMI – Dmitrowo, DOBR – Dobrąg, DBRZ – Dobrzyń, EŁC – Ełckie, GIER – Gieret, GIL – Gil, GREM – Gremzdy, HAR – Harsz, HOŁ – Hołny, JAŁ – Jałowo, JEM – Jemieliste, KAM – Kamenduł, KIER – Kiersuń (Korsuń), KRSZ –Kiersztanowskie, KOP – Kopane, KOR – Kortowskie, KRZ – Krzywe, KUK – Kukowino, LEM – Lemięt, LES – Leszczewek, LIN – Linowskie, ŁAZ – Łazduny, MAŁ – Małe, MIER – Mieruńskie, MLE – Mleczówka, MOR – Morliny, OLEM – Oleckie Małe, ORŁO – Orło, PŁA – Płaskie, POBŁ –Pobłędzie, POM – Pomorze, POZ – Pozorty, PRZE – Przerośl, RUS – Ruskie, RYDZ – Rydzówka, RYN – Ryngis, SAR – Sarąg, SAS – Sasiny, SEJ – Sejwy, SIEK – Siekierowo, SIL – Silec, SKA –Skanda, SKB – Skazdubek, SOŁ – Sołtmany, SUN –Sunowo, SZÓS – Szóstak, SZTA – Sztabinki, SZUR – Szurpiły, SZWA – Szwałk Mały, TAB – Tabórz, TOB – Tobołowo, TYR – Tyrsko, WYM – Wymój, ZAJ – Zajdy, ZEL – Zelwa, ŻAB – Żabińskie, ŻUB – Żubrowo

between Polish/Lithuanian/Belarussian/Russian border and the Vistula river valley (Fig. 1). The landscape in this part of Europe is dominated by glacial landforms from the Pomeranian phase of the Weichselian glaciation (Marks, 2012) and consequently, the lakes are of glacial origin (Pochocka-Szwarc, 2010; Kondracki, 2013). The Late Weichselian maximum ice sheet limit in Poland was time-transgressive and occurred at 24-19 kyrs BP becoming younger to the east (Pochocka-Szwarc, 2010; Marks, 2012). The geological substrate for lakes in this region consists of glacial till and varigrained glaciofluvial clastic sediments (Pochocka-Szwarc, 2013). The climate in the area is temperate, the average July temperature is 19.0 °C, while in January is between -2.7 °C in the southern Warmia to -3.4 °C in the Suwałki Lake District. The average precipitation is from 699 to 734 mm/yr, most of which occurs during the summer (pl.climate-data.org). The lakes of study are small to medium size and moderately deep with only a few having maximum depth below 10 m (Tab. 1). They also differ in terms of catchment lithology, land use and trophic state (Tab. 1). The latter displays gradient from oligotrophic via eutrophic to dystrophic lakes (Jańczak, 1999; Jekatierynczuk-Rudczyk et al., 2014).

Table 1. Physical features (range) of the lakes studied. Morphometric parameters were taken from The Atlas of Polish Lakes (Jańczak, 1999). Catchment characteristics were obtained from Corine Land Cover (CLC) 2018 (Corine, 2018) and Geological Map of Poland (GMP) 1:500,000 (Marks et al., 2006) with the procedure described by Jasiewicz et. al. (2022)

Name	Unit	Value range Min-Max
Elevation	m a.s.l.	63.4-254.7
Lake area	km^2	0.14-5.00
Lake maximum depth	m	6.5-55.8
Lake average depth	m	3.6-15.0
Basin area	km^2	1.00-131.48
Sand	%	0-100.0
Till	%	0-100.0
Clays	%	0-43.3
Organic	%	0-51.7
Urbanized area	%	0-30.5
Agriculture area	%	2.6-91.0
Forested area	%	0.3-97.2
Wetlands area	%	0.0-43.0

Methods

Each lake was sampled once during the summer field campaigns in July 2018, 2019 and 2020. Epilimnion water samples were collected 1 m below the water surface with UWITEC water sampler of 2 liter capacity, from the deepest part of the lake. Samples were stored unpreserved in darkness in a cool room until chemical analysis. The several water parameters were measured in laboratory: total phosphorus (P_{tot}), sulfates (SO_4^{2-}), bicarbonates (HCO_3^-), chlorides (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+).

Total phosphorus concentration, P_{tot} ($\mu g \cdot L^{-1}$) was analyzed spectrophotometrically (Nanocolor VIS; Macherey-Nagel) with ammonium molybdate after mineralization with HNO_3 and H_2O_2 in UV Mineral 6.1. The ion composition of water was analysed in the samples filtered through 0.45 μm membrane disc filters. Cl^- and SO_4^{2-} were measured with ion-exchange chromatography (ICS2000 Dionex equipped with IonPac AS18 column) and HCO_3^- was determined via titration with 0.05M HCl with regard to phenolophtalein (to pH = 8.3) and methyl orange (to pH = 4.5). Na^+, K^+, Mg^{2+} and Ca^{2+} were measured using atomic absorption spectroscopy with NovAA 300 device (Analytik Jena, Germany). Analytical quality was ascertained with CRMs (Cranberry-05 and NWHAMIL-20.2, Battle-02, Huron-20 and Trois-94).

Along with water sampling the Secchi depth (SD; m) was assessed using a standard disk. On-site measurements at 1m depth of physical-chemical parameters (lake water temperature (t), electric conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), chlorophyll-*a* (Chl-*a*), phycocyanin (PC))

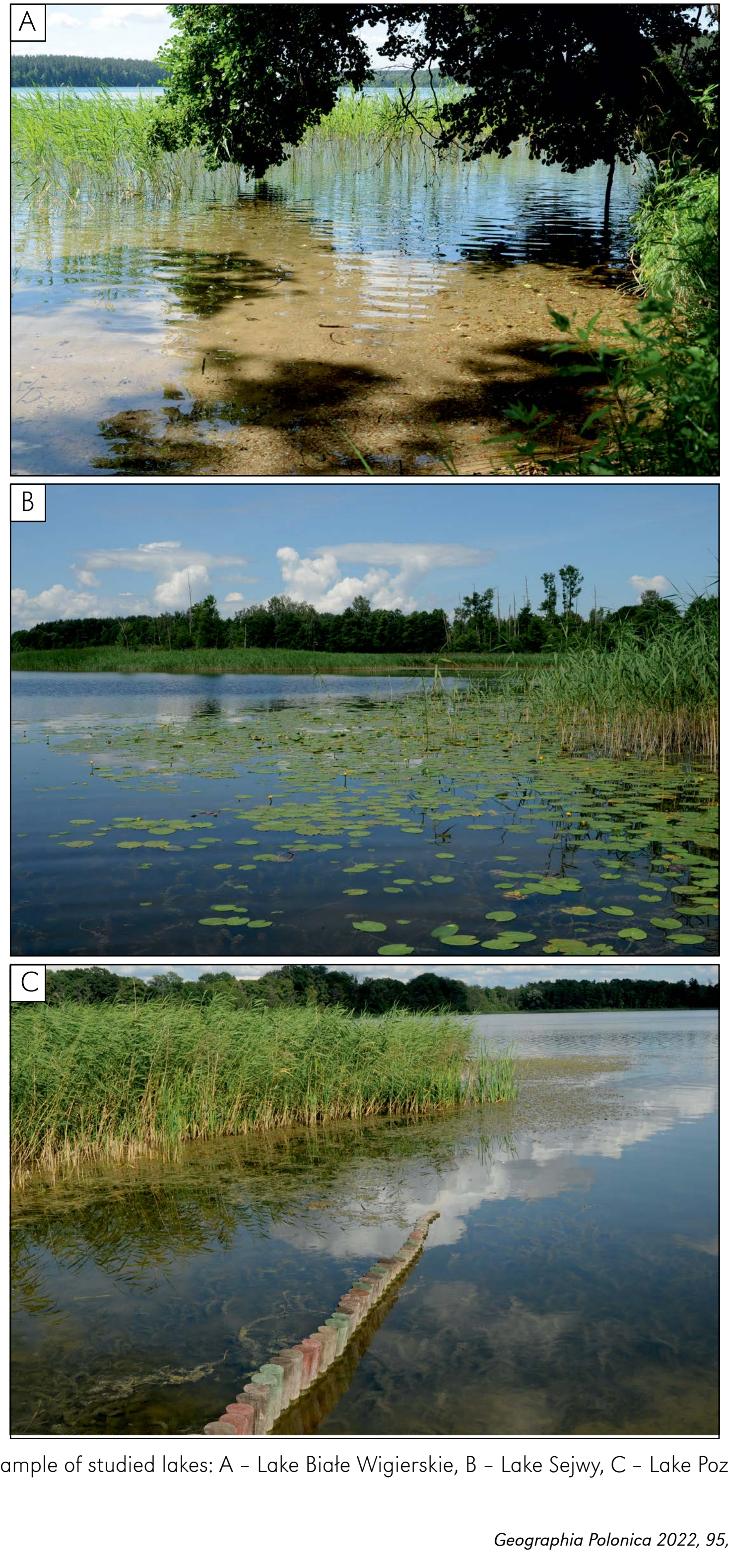


Figure 2. Example of studied lakes: A – Lake Białe Wigierskie, B – Lake Sejwy, C – Lake Pozorty

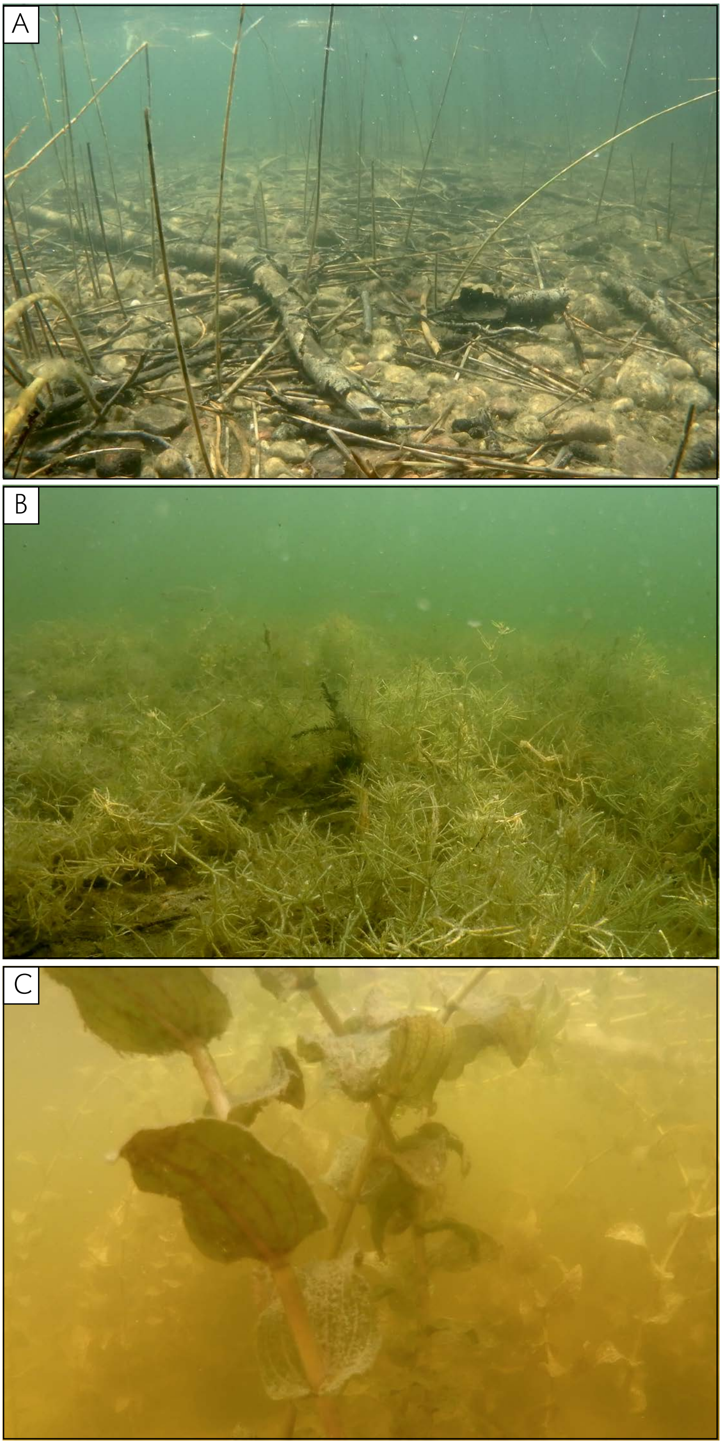


Figure 3. Underwater pictures of selected lake littoral zone: A – Lake Białe Wigierskie, B – Lake Sztabinki, C – Lake Sejwy

were performed using a multiparameter probe EXO 1 by YSI calibrated and checked with certified reference material (Harbour water, NWHAMIL-20.2). The reference temperature used for calculating temperature compensated electric conductivity is 25°C. In order to get information on the temperature and oxygen stratification in each lake measurements were conducted in the entire water column every 1 m. The stratification profiles of oxygen, temperature, chlorophyll-*a*, electric conductivity were prepared using C2 freeware (Juggins, 2007).

The sediment samples (upper 4 cm) which were used to assess sedimentary species composition of Cladocera and diatoms were also taken from the deepest part of the lake, alike the water sample, using Limnos sediment corer. The deepest point is regarded as representative for the whole lake for limnological and paleolimnological studies (Apolinarska et al., 2020; Davidson et al., 2010; Frey, 1988; Heggen et al., 2012; Hernández-Almeida et al., 2017; Tylmann et al., 2012). In case of a few lakes of complex morphology (Lake Ełckie, Żabińskie, Łazduny, Kamenduł, Kortowskie, Szurpiły, Dmitrowo, Długie), the bottom sediments were sampled in second deepest site.

In order to conduct subfossil Cladocera analysis, the 2 cm^3 of homogenized fresh sample from each lake was prepared in the laboratory according to the standard procedure described by Frey (1986). Samples were first treated with hot 10% KOH and HCl in order to remove carbonates. Chemical treatment was followed by sieving with a 38 μm mesh size. Microscope slides were examined with a light microscope under magnifications of ×100, ×200, and ×400. All skeletal elements (head shields, shells, and postabdomens) were counted until 70-100 individuals were found, which is regarded as an adequate number to characterize the assemblages (Kurek et al., 2010). Identification of Cladocera remains was based on the key by Szeroczyńska and Sarmaja-Korjonen (2007). Distinction of the Eubosmina species was based on publication of Faustová et al. (2011) and Błędzki & Rybak (2016).

Diatom remains were extracted from 2 cm^3 of fresh sediment sample with 30% HCl and 30% H_2O_2, using the disintegration method according to Battarbee (1986). At least 500 diatom valves per sample were counted. For the species identification the keys by Bahls et al. (2018); Hoffmann et al. (2011); Krammer and Lange-Bertalot (2008a, 2008b, 2010, 2011); Lange-Bertalot et al. (2011); Lange-Bertalot and Genkal (1999); Lange-Bertalot and Metzeltin (1996) were used. All of the taxonomic data was updated by the AlgaeBase (www.algaebase.org) (Guiry & Guiry, 2022).

Results

The studied lakes differed considerably from each other with regard to morphometric features (Tab. 1), however it should be underlined that small lakes were preferably chosen, because of their high sensitivity to environmental changes. Despite that all the lakes were located in post-glacial landscape their catchments displayed different lithologies from primarily fine-grained (up to 100% coverage by till and/or clay) to predominantly coarse-grained (up to 100% coverage by sands) with appreciably high shares of paludified areas. The catchments were usually weakly urbanized. The highest share of urbanized areas of 30.5% was in Lake Kortowskie catchment.

Even more important for the current study was that the lakes studied covered appreciably wide gradient of physical-chemical water parameters during summer maximum of biological activity in temperate lakes (Tab. 2; Fig. 4-9). The key variables measured were (i) bulk water mineralisation-related indicators (EC/TDS, Na^+, Ca^{2+}), (ii) red-ox and alkalinity conditions (pH, O_2 concentration, HCO_3^-) and (iii) trophy-related indicators such as total phosphorus (TP), chlorophyll-*a* (Chl-*a*) and Secchi depth (SD) (Fig. 4),

On the basis of the Gibbs' diagram (Gibbs', 1970) (Fig. 10) it appears that water chemistry in the lakes were primarily shaped by chemical weathering reactions, which can

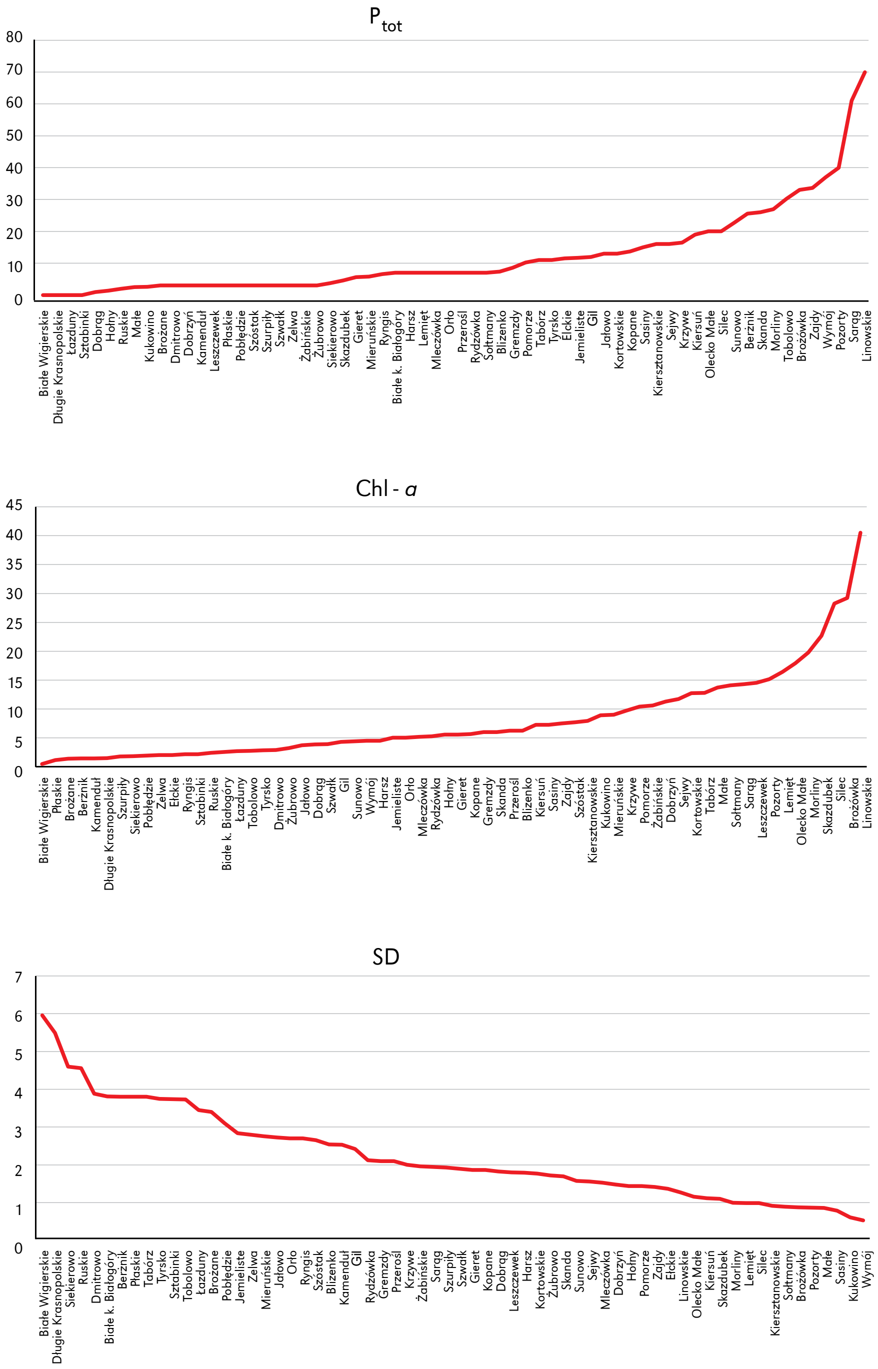


Figure 4. The parameters of the selected water properties of studied lakes measured at 1 m depth: P_{tot} (total phosphorus; µg/L), Chl-*a* (chlorophyll-*a*; µg/L), SD (Secchi disk; m)

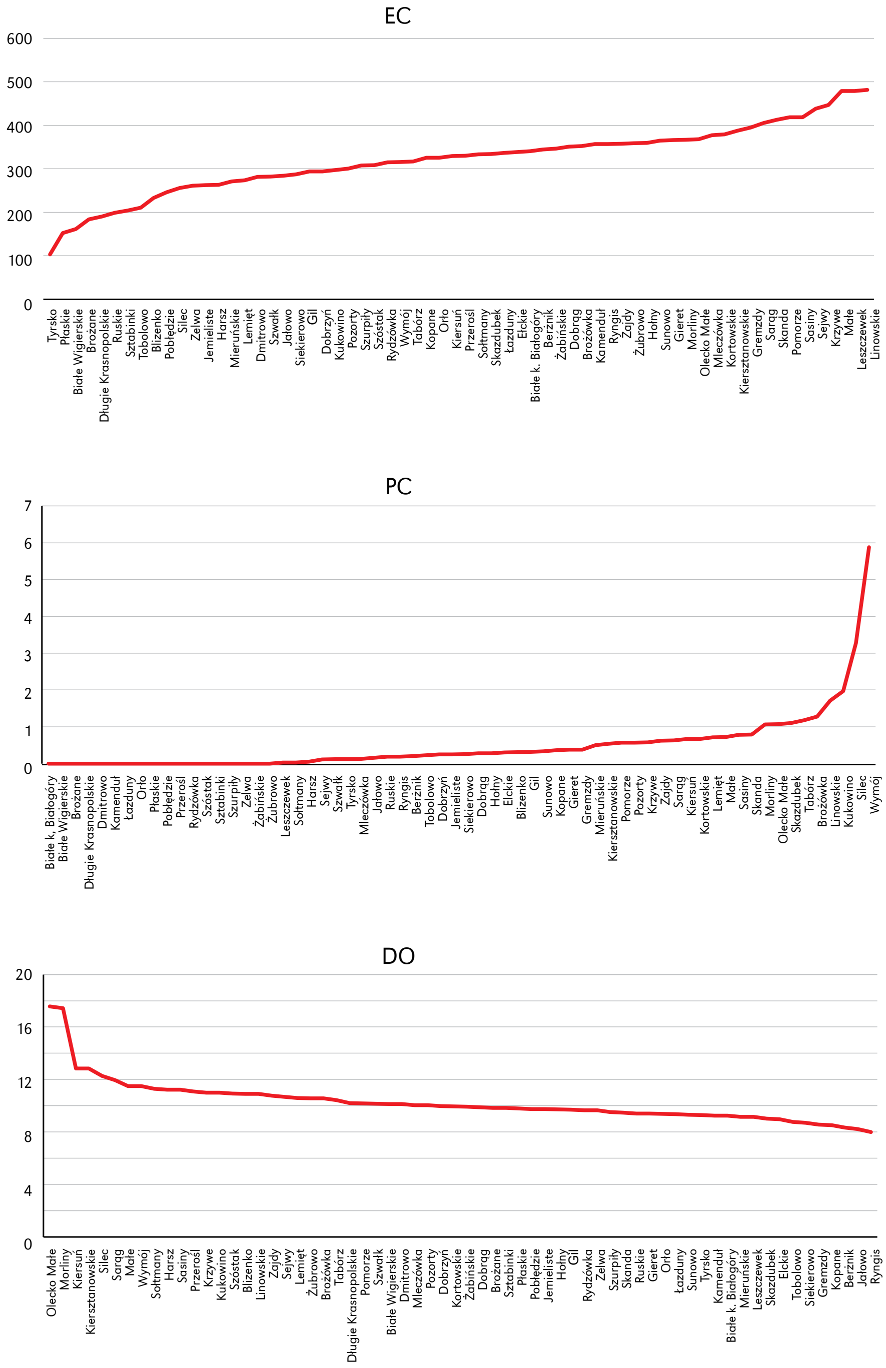
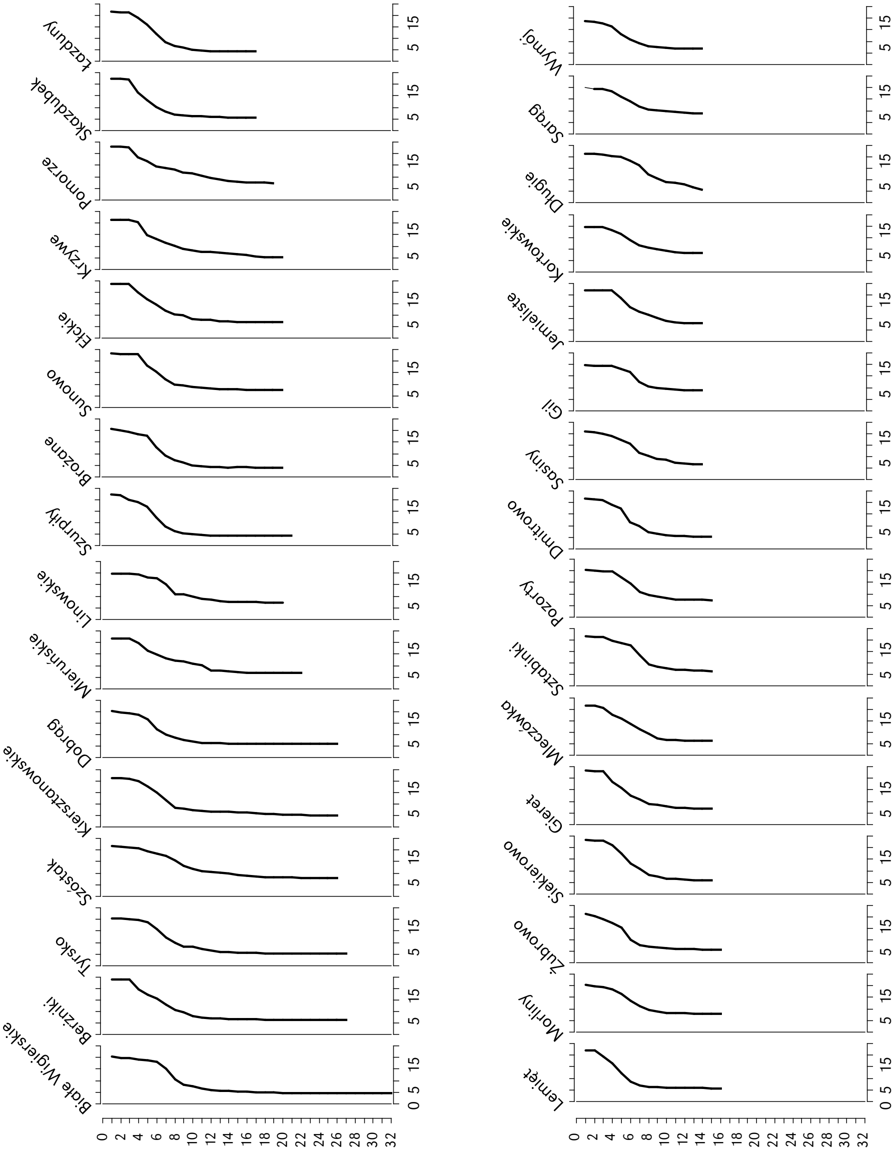


Figure 4. The parameters of the selected water properties of studied lakes measured at 1 m depth: EC (electrical conductivity; µS/cm), PC (phycocyanin; µg/L), DO (dissolved oxygen; mg/L)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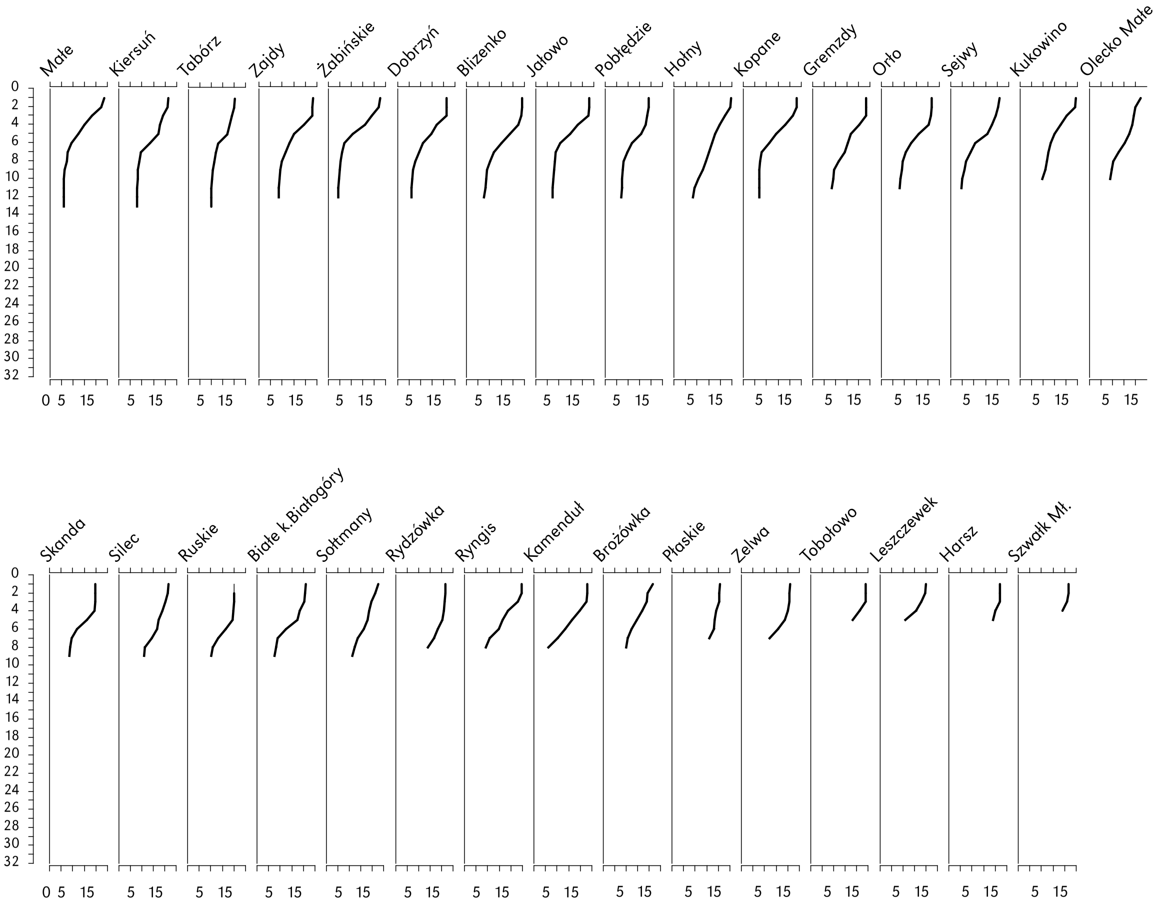
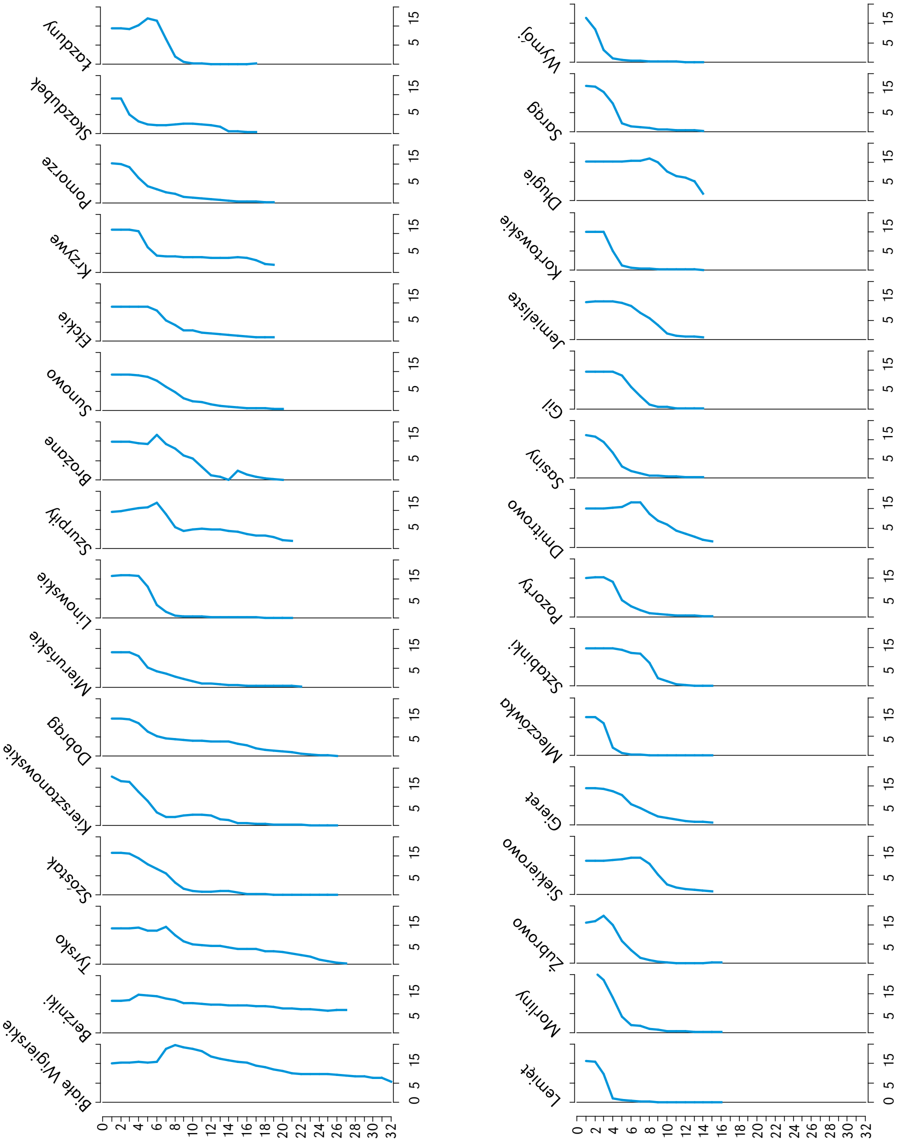


Figure 5. The vertical distribution of temperature (t) in studied lakes during summer stagnation period. The x axis represents the rage of t values (°C), y axis represents depth (m)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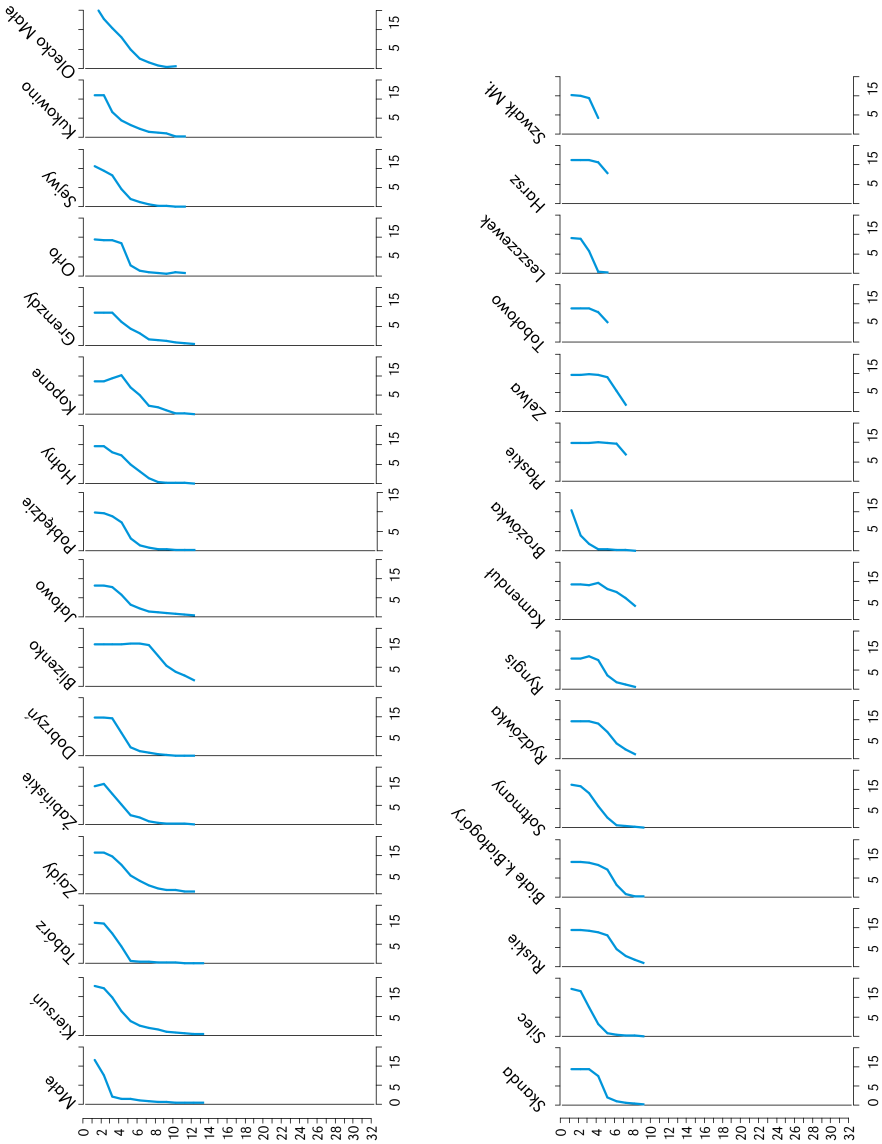
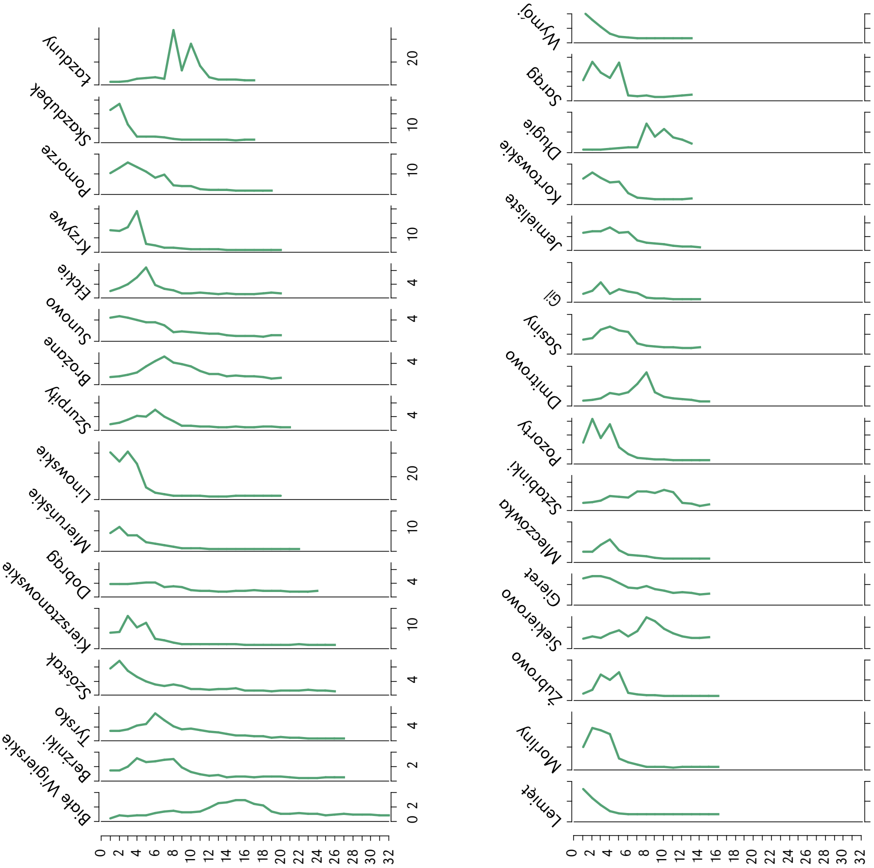


Figure 6. The vertical distribution of dissolved oxygen (DO) in studied lakes during summer stagnation period. The x axis represents the rage of DO values (mg/L), y axis represent depth (m)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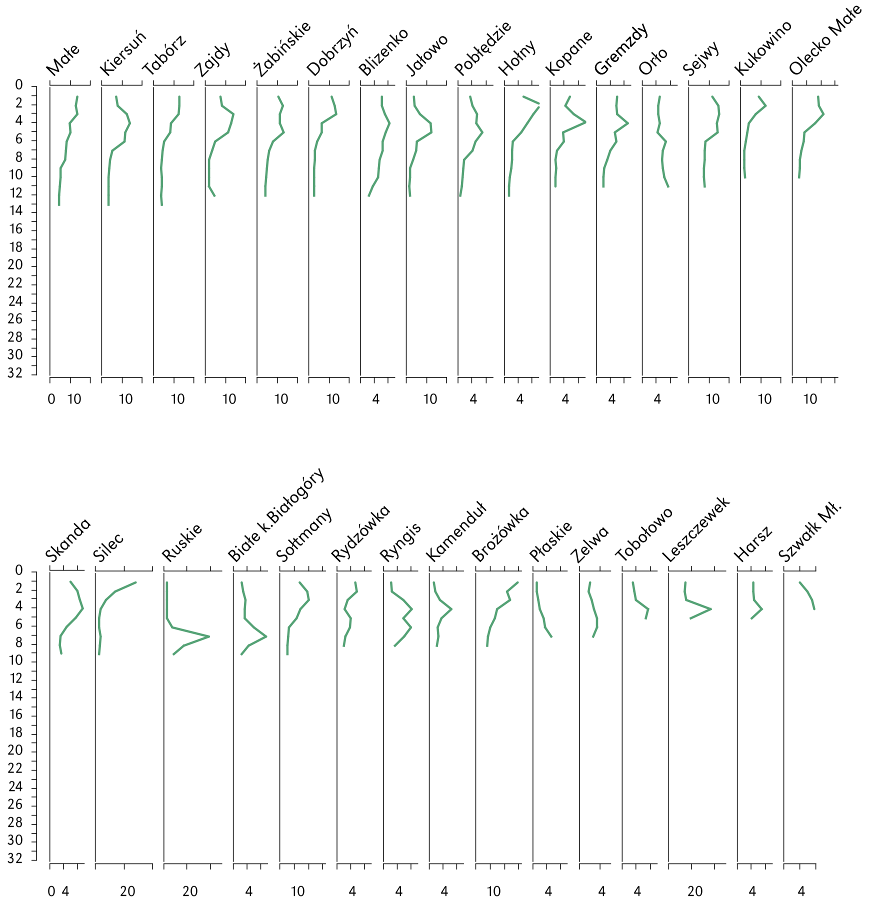
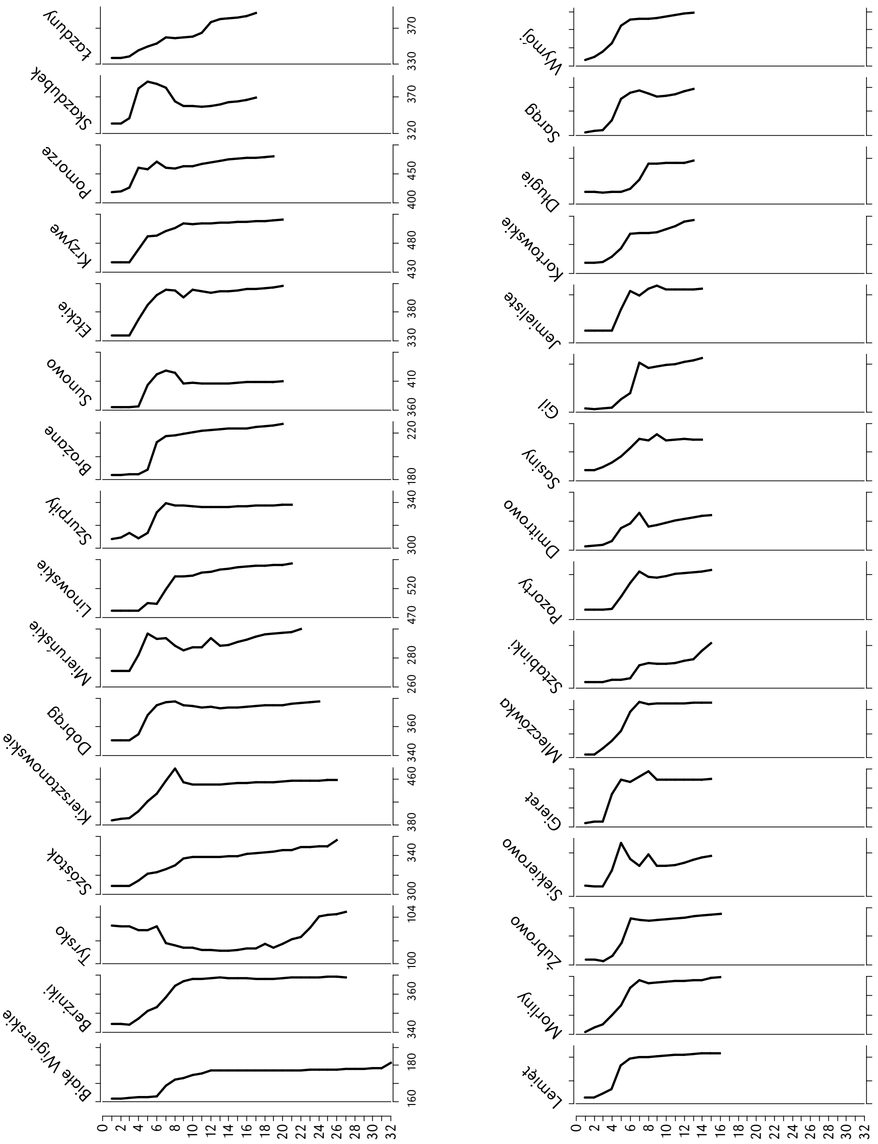


Figure 7. The vertical distribution of chlorophyll-*a* (Chl-*a*;) in studied lakes during summer stagnation period. The x axis represents the rage of Chl-*a* values (µg/L), y axis represents depth (m)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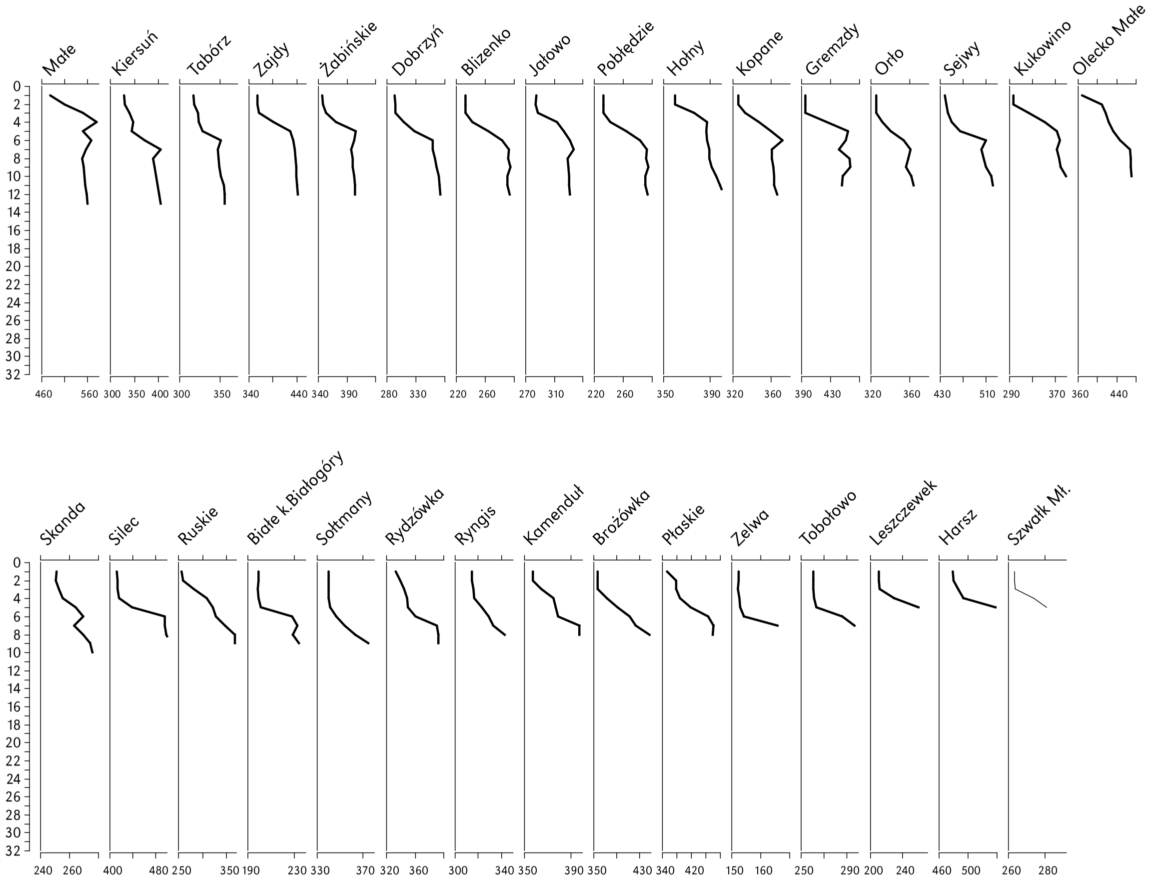

Figure 8. The vertical distribution of electrical conductivity (EC) in studied lakes during summer stagnation period. The x axis represents the range of EC values (μS/cm), y axis represents depth (m)

Table 2. Hydrochemical parameters of lake waters (range) based on in-situ measurements and laboratory analyses

Name	Unit	Value range Min-Max
Total phosphorus (P_{tot})	µg/L	0-70
Secchi depth (SD)	m	0.53-5.96
Chlorophyll-*a* (Chl-*a*)	µg/L	0.45-40.53
Phycocyanin (PC)	µg/L	0.00-5.88
Conductivity (EC)	µS/cm	103.3-481.4
Total dissolved solids (TDS)	mg/L	99.0-315.0
Dissolved oxygen (DO)	mg/L	7.99-17.57
Temperature (t)	°C	18.8-24.7
pH	pH	7.29-8.96
N_{tot}*	mg/L	0.78-12.30
HCO_3^-	mg/L	52.47-308.7
Cl-*	mg/L	2.90-93.3
Ca	mg/L	12.31-80.83
Na	mg/L	1.68-25.54

be found typical of temperate lakes. The contribution from evaporation and especially from atmospheric precipitation was very weak. The former showed some, albeit minor, importance in Lake Sarąg, L. Skanda, L. Linowskie, L. Kiersztanowskie. It seems however, that the enhanced TDS and Na/Na+Ca values in these lakes were owing to cultural eutrophication rather than due to enhanced evaporation.

Epilimnetic waters in the lakes were well oxygenated, as expected for surface layers of lakes, however O_2 concentrations changed in a broad range (Tab. 2). O_2 variability seems to be related to bioproductivity. The highest DO values (~17.5 mg L^{-1}) were noted in two lakes with high Chl-*a* (Olecko Małe and Morliny). Lake water pH was alkaline albeit alkalinity (in terms of HCO_3^-), and thus pH buffering capacity, varied greatly from low values in Lake Tyrsko to high values in L. Leszczewek.

Total phosphorus (P_{tot}) is considered as a main limiting factor of biological productivity in lakes (Wetzel, 2001). The P_{tot} gradient in studied lakes was wide (Fig. 4) ranging from very low values (nearly 0) typical of low trophic state and removal of P by phytoplankton in the lake to 70 µg L^{-1} typical of eutrophic conditions (OECD, 1982). The Chl-*a* acts as a phytoplankton community biomass index and is positively related to the P_{tot} availability (Kalff, 2002). However, high P_{tot} values not always results in high Chl-*a* values (eg.: lakes Wymój, Zajdy). The SD values is broadly used to characterize water transparency however it is also closely related to water trophic state because light penetration depth in lake water columns are very often determined by the occurrence of phytoplankton (Kalff, 2002; OECD, 1982). On the other hand, the relationship between SD and trophic state can be modified by the occurrence of dissolved organic matter as well as inorganic suspension (Kalff, 2002; Borowiak, 2015). The measured SD range from considerably high values of ca. 6.00 m in the lake Białe Wigierskie to as low as 0.5 m in Lake Wymój. The very low transparency in the latter can be attributed to the abundance of cyanobacteria, as evidenced by highest phycocyanin values (PC) of 5.88 µg L^{-1} (Brient et al., 2008).

The vertical hydrochemical profiles provide additional information on the lake functioning. The summer hydrochemical profiles show vertical thermal stratification in the lake water columns (Fig. 5). In addition, in lakes > 10 m deep the water column was stratified into epi-, meta- and hypolimnion. In lakes < 10 m deep the stratification was rather weak albeit temperature gradients were present from the top to the bottom. Based on temperature distribution it appeared that the thickness of epilimnion varied between c.a. 2 m in Lake Kukowino and Małe to c.a. 7 m in L. Białe Wigierskie. Metalimnion, where thermocline (defined as ≥ 1°C difference per 1 m depth) was located, was 3-9 m-thick. The minimum thickness occurred in L. Białe Wigierskie, the deepest lake in our data set. On the other hand, the highest thickness of the metalimnion was noted in Lake Linowskie (Fig. 5), where also the highest value of epilimnetic TP and Chl-*a* were measured. Among many factors controlling the thickness of epi- and metalimnion the wind fetch seems to be of crucial importance, however, some influence from lake area and water transparency was also reported (Kalff, 2002). It was shown that the abundance of solid particles in suspension hampers penetration of the water column by solar energy thus limiting the depth of heat transfer.

Midsummer oxygen (DO) profiles showed overall O_2 downward decreasing trends in most lakes studied (Fig. 6). Clinograde O_2 curves predominated with only few exceptions. Near bottom waters were usually anoxic/suboxic. Oxic conditions in the bottom part of the water column were found in deep, stratified lakes such as L. Białe Wigierskie and Berżniki, as well as in several shallow lakes e.g L. Płaskie, L. Zelwa, L. Tobołowo (Fig. 6). In the two deep lakes the presence of O_2 is related to nutrient-poor conditions therein (Jasiewicz et al., 2022) and thus low O_2 consumption for organic matter degradation. The oxic conditions throughout the whole water column in few shallow lakes was presumably owing to low water depth and polymictic character, as well as low trophic status. In 6 out of 64 studied lakes (Białe Wigierskie, Tyrsko, Szurpiły, Brożane, Łazduny, Dmitrowo; Fig. 9) we found positive heterograde O_2 distribution. This type of distribution is characterized by a maximum oxygen concentration occurring in metalimnion. The DO maxima are formed both by biological processes resulting from photosynthethic O_2 production, as well as physical processes such as warming of gasses trapped below the thermocline (Wilkinson et al., 2015). The co-occurrence of DO and Chl-*a* maxima in L. Brożane suggest that O_2 peak in metalimnion formed as a result of photosynthethic production. In other 5 lakes, however, DO and Chl-*a* show different patterns, thus, suggesting physical forcing on DO maximum formation (Wilkinson et al. 2015). This process presumably involves the offshore O_2 transport by water currents into deeper layers Kalff (2002).

Vertical distribution of chlorophyll-*a* (Chl-*a*) in the water columns vary greatly between lakes and show very week relationships to measured hydrochemical parameters. However, in most of the lakes studied maximum values occurred in the epilimnion (Fig. 7). Provided that chlorophyll-*a* was found to be very labile compound, which could be microbially degraded within a time span of days to hours (Rydberg et al., 2020), we presume that its distribution in the water column indicates the zones of its in-situ production. Interestingly, in 10 stratified lakes the maximum Chl-*a* values occurred in meta- or hypolimnion indicating forming of deep chlorophyll maxima (DCM) or deep chlorophyll layer (DCL). The primary production within DCM may contribute to large amount (~60%) of total algal production in the lake (Camacho, 2006; Scofield, Watkins, Osantowski, & Rudstam, 2020). The mechanisms responsible for DCL formation are various (Camacho, 2006; Scofield, 2020), but its depth increase with water transparency (Scofield, 2020). In low productivity lake, Białe Wigierskie (SD 5.96 m), DCL occurs in oxygenated hypolimnion at 11,5-18,5 m depth. Whereas in Lake Łazduny (SD 3.45 m) it was located within a layer with a very low oxygen concentration at 7.5-11.5 m. We hypothesize that occurrence of DCL in anoxic waters may be caused by the presence of chlorophyllous phototrophs conducting anoxygenic photosynthesis (Camacho, 2006; Scofield, 2020).

Together with temperature electrical conductivity (EC) is known to reflect density stratification of lake waters (Fig. 8). As a rule, when vertical stratification is established, EC shows a downward increase and the EC gradient zone occurs in metalimnion. The difference between low-EC epilimnion and higher EC bottom/hypolimnetic waters is owing to the predominance of photosynthesis and $CaCO_3$ precipitation over respiration in the surface waters while in bottom waters organic matter degradation and carbonate dissolution became more important (Wetzel, 2001). With only few exceptions, the lake studied follow the above well-established tendency. However, in L. Kiersztanowskie, L. Sunowo, L. Skazdubek, L. Siekierowo, L. Dmitrowo and L. Sarąg EC culminations occurred in metalimnetic waters (Fig. 8). We speculate that

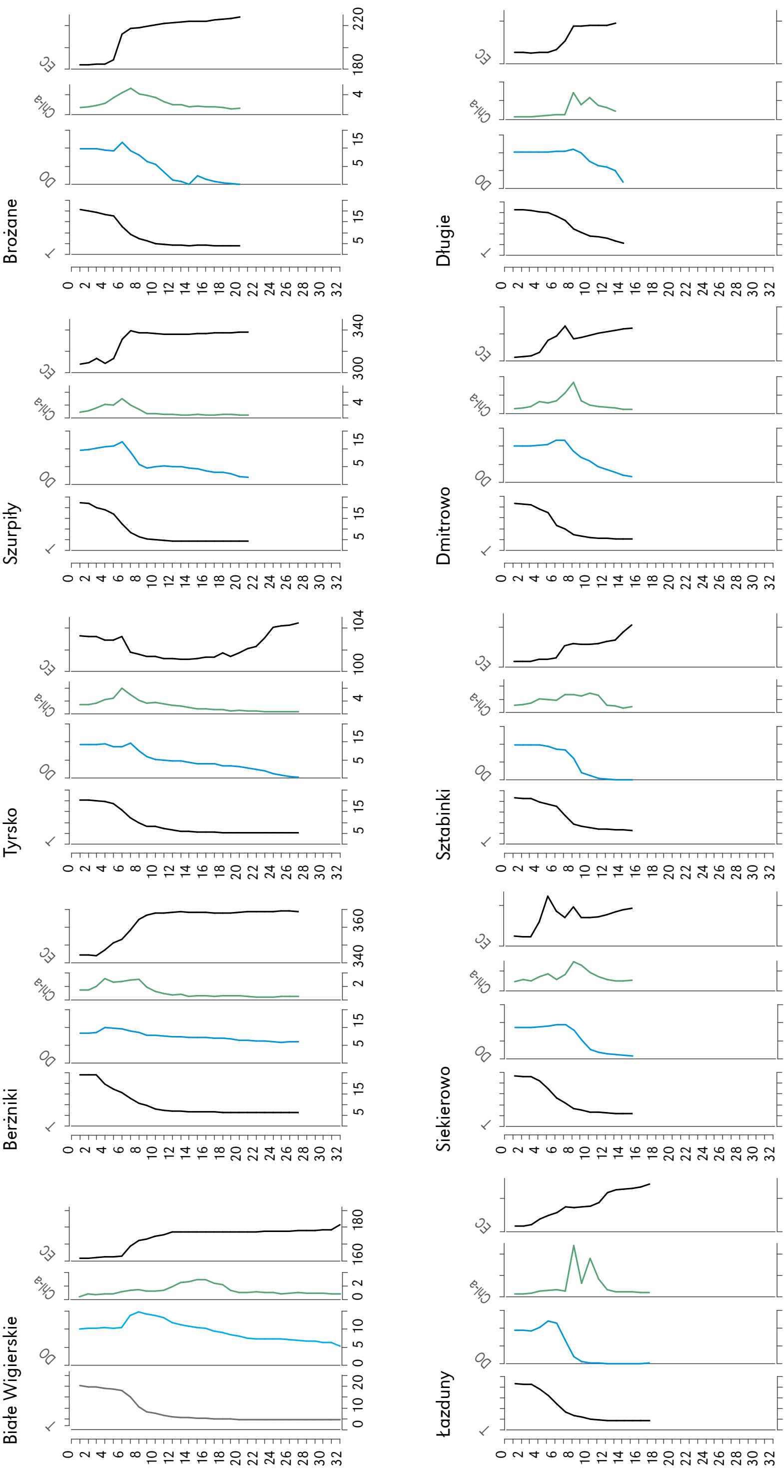

Figure 9. The combined results of vertical distribution of temperature (t; °C), dissolved oxygen (DO; mg/L), chlorophyll-*a* (Chl-*a*; µg/L), electrical conductivity (EC; µS/cm) for selected lakes during summer stagnation period

this unusual EC distribution can be related to enhanced oxidation of anoxic chemical species (e.g. CH_4) which is often found in the oxycline (Schubert et al., 2010).

Subfossil Cladocera assemblage

In the surface sediments of 64 studied lakes the remains of 46 Cladocera species were found. The number of species in single sample varied from 24 in L. Ruskie (mesotrophic) to only 8 in L. Małe (eutrophic). Two species were present in all studied lakes: *Chydorus sphaericus* cf. and *Bosmina longirostris*. *Chydorus sphaericus* cf. is known as a highly adaptive species and therefore one of the most widespread among freshwater crustaceans. It inhabits mostly littoral zone; however, it is often found in pelagial as it can feed on filamentous algae (Błędzki & Rybak, 2016). *Bosmina longirostris* is a worldwide distributed species that can adapt and survive in most harsh conditions (Adamczuk, 2016). It is pelagic species but it also displays ability to live among plants in littoral zone (Błędzki & Rybak, 2016). Both, *Chydorus sphaericus* cf. and *Bosmina longirostris* were most frequent Cladocera species in zooplankton of 410 reservoirs in Central and Western Poland (Kuczyńska-Kippen, 2020). Other commonly occurring species in studied lakes were *Bosmina* (E.) *coregoni* (in 61 lakes, maximum share 40% in Lake Berżniki), *Bosmina* (E.) *longispina* (in 60 lakes, maximum share 34% in Lake Siekierowo), *Alona rectangula* (in 60 lakes, maximum share 11% in Lake Tabórz), *Alonella nana* (in 57 lakes, maximum share 9% in Lake Kopane), *Acroperus harpae* (in 55 lakes, maximum share 7% in Lake Kopane). Four rare Eubosmina were recognized, that are the youngest species that appeared during a recent speciation (Błędzki & Rybak, 2016): *Bosmina* (E.) *thersites* (found in 15 lakes, maximum share 26% in Lake Pobłędzie), *Bosmina* (E.) *gibbera* (3 lakes, maximum share 5% in Lake Pozorty), *Bosmina* (E.) *reflexa* (34 lakes, maximum share 15% in Lake Rydzówka), *Bosmina* (E.) *longicornis* f. *berolinensis* (20 lakes, maximum share 7% in Lake Dobrąg).

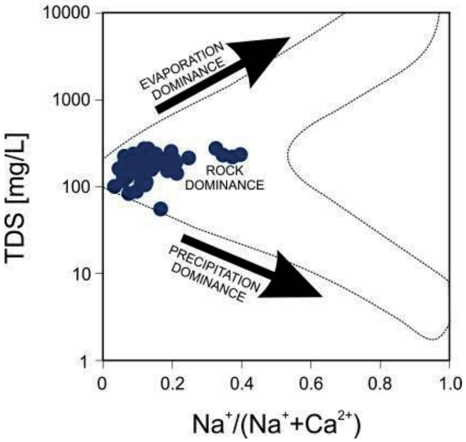

Figure 10. Gibbs diagram for the lakes studied. The diagram is used to show the major processes affecting lake water chemistry. From the diagram it appears that lake water composition in Polish lowland lakes is primarily shaped by weathering reactions in the substrate. The influence from evaporation (upper edge) and atmospheric precipitation (lower edge) is negligible

Subfossil diatoms

In total, 129 diatom species, including varies and forms were identified. The structure of diatom assemblages in terms of habitat was very diverse. Among the lakes studied there were those in which planktonic diatoms predominated and the lakes with high shares of tychoplanktonic (i.e. accidental plankton/pseudoplankton) species. The latter feature in lakes is a result of vertical water mixing and sediment resuspension, which causes benthic diatoms to detach from the lake floor and float in the water (Kawecka & Eloranta, 1994; Witkowski et al., 2009).

The most abundant planktonic species were *Aulacoseira italica*, *Aulacoseira granulata*, *Aulacoseira ambigua*, *Pantocsekiella comensis*, *Stephanodiscus parvus*. The most abundant tychoplanktonic species were *Pseudostaurosira brevistriata*, *Staurosira construens*, *Staurosirella lapponica*. Sixteen species were rare (occurring only once), while 37 species (28.7% all diatoms) occurred at low (< 1%) relative abundance. Thirty-one species were abundant (i.e. ≥ 5% maximum relative abundance in one or more samples), while five (*Stephanodiscus parvus*, *Pantocsekiella comensis*, *Aulacoseira italica*, *Staurosira construens*, *Staurosirella lapponica*) were widespread (i.e. occurring in ≥ 50%). *S. parvus*, a diatom with hypertrophic affinities (Kirilova et al., 2011), was recorded in high relative abundance and occurred in 56 sites (max 75.7% with maximum relative abundance in L. Orło). *S. parvus* was accompanied by *P. comensis*, a diatom with oligo-mesotrophic affinities (Carayon et al., 2019) and occurred in 54 sites (max 70.6% in L. Łazduny). *A. italica*, acting as oligo-mesotrophic species (Krammer & Lange-Bertalot, 2008b), occurred in 9 sites (max 61.9% in L. Jałowo). *S. construens,* epiphytic species found in more or less calcium-rich lakes and flowing waters, occurred in 49 sites (max 59.1% in L. Białe Wigierskie). Moreover, *S. construens* is most abundant in non-stratified lakes (Hoffmann et al., 2011; Bąk et al., 2012). *S. lapponica* is a diatom with affinity to oligotrophic, Ca-enriched lowland lakes (Hoffmann et al., 2011; Carayon et al., 2019) This species occurred in 16 lakes (max. abundance 56.9% in L. Dmitrowo).

Conclusions

The current paper provides an overview of the lakes included in a database to be used to calculate a transfer function for quantitative reconstructions of trophic state of temperate lakes on the basis od subfossil Cladocera. Despite that the primary criterion for selection of the lakes for this study was their present-day trophic state, the lakes represented a wide array of morphometries, hydrodynamic conditions, catchment characteristics and anthropogenic disturbances of the ecosystem. Therefore, the data basis presented seem to offer a comprehensive information on the variability of Polish lakes which may be of interest to limnologists and hydrobiologists.

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Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

References

Adamczuk, M. (2016). Past, present, and future roles of small cladoceran *Bosmina longirostris* (O. F. Müller, 1785) in aquatic ecosystems. *Hydrobiologia*, *767*(1), 1-11. https://doi.org/10.1007/s10750-015-2495-7

Apolinarska, K., Woszczyk, M., & Obremska, M. (2012). Late Weichselian and Holocene palaeoenvironmental changes in northern Poland based on the Lake Skrzynka record. *Boreas*, *41,* 292-307. https://doi.org/10.1111/j.1502-3885.2011.00235.x

Apolinarska, K., Pleskot, K., Pełechata, A., Migdałek, M., Siepak, M., & Pełechaty, M. (2020). The recent deposition of laminated sediments in highly eutrophic Lake Kierskie, western Poland: 1 year pilot study of limnological monitoring and sediment traps. *Journal of Paleolimnology*, *63*(4), 283-304. https://doi.org/10.1007/s10933-020-00116-2

Bahls, L., Boynton, B., & Johnston, B. (2018). Atlas of diatoms (Bacillariophyta) from diverse habitats in remote regions of western Canada. *PhytoKeys*, *186*(105), 1-186. https://doi.org/10.3897/phytokeys.105.23806

Bąk, M., Witkowski, A., Żelazna-Wieczorek, J., Wojtal, A. Z., Szczepocka, E., Szulc, K., & Szulc, B. (2012). Klucz do oznaczania okrzemek w fitobentosie na potrzeby oceny stanu ekologicznego wód powierzchniowych w Polsce. *Biblioteka Monitoringu Środowiska*, 452.

Battarbee, R. W. (1986). Diatom analysis. In B. E. Berglund (Ed.), *Handbook of Holocene paleoecology and paleohydrology* (pp. 527-570). London: John Wiley and Sons, ltd.

Battarbee, R. W., Jones, V. J., Flower, R. J., Cameron, N. G., Bennion, H., Carvalho, L., & Juggins, S. (2001). Diatoms. In J. P. Smol, H. J. B. Birks, & W. M. Last (Eds.), *Tracking Environmental Change Using Lake Sediments. Vol. 3, Terrestrial, Algal, and Siliceous Indicators* (pp. 155-202). Kluwier Academic Publishers.

Bennion, H., Battarbee, R. W., Sayer, C. D., Simpson, G. L., & Davidson, T. A. (2011). Defining reference conditions and restoration targets for lake ecosystems using palaeolimnology: A synthesis. *Journal of Paleolimnology*, *45*, 533-544. https://doi.org/10.1007/s10933-010-9419-3

Błędzki, L. A., & Rybak, J. I. (2016). *Freshwater Crustacean Zooplankton of Europe*: *Cladocera & Copepoda (Calanoida, Cyclopoida) Key to species identification, with notes on ecology, distribution, methods and introduction to data analysis.* Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-29871-9

Borowiak, D. (2015). Optical properties of Polish lakes: The Secchi disc transparency. *Limnological Review*, *14*(3), 131-144. https://doi.org/10.1515/limre-2015-0003

Brient, L., Lengronne, M., Bertrand, E., Rolland, D., Sipel, A., Steinmann, D., & Bormans, M. (2008). A phycocyanin probe as a tool for monitoring cyanobacteria in freshwater bodies. *Journal of Environmental Monitoring*, *10*(2), 248-255. https://doi.org/10.1039/B714238B

Brodersen, K. P., Whiteside, M. C., & Lindegaard, C. (1998). Reconstruction of trophic state in Danish lakes using subfossil chydorid (Cladocera) assemblages. *Canadian Journal of Fisheries and Aquatic Sciences*, *55*(5), 1093-1103. https://doi.org/10.1139/cjfas-55-5-1093

Camacho, A. (2006). On the occurrence and ecological features of deep chlorophyll maxima (DCM) in Spanish stratified lakes. *Limnetica*, *25*(1), 453-478. https://doi.org/10.23818/limn.25.32

Carayon, D., Tison-Rosebery, J., & Delmas, F. (2019). Defining a new autoecological trait matrix for French stream benthic diatoms. *Ecological Indicators*, *103*(December 2018), 650-658. https://doi.org/10.1016/j.ecolind.2019.03.055

Chalie, F., & Gasse, F. (2002). Late Glacial-Holocene diatom record of water chemistry and lake level change from the tropical East African Rift Lake Abiyata (Ethiopia). *Palaeogeography, Palaeoclimatolog, Palaeoecology*, *187*(3-4), 259-283. https://doi.org/10.1016/S0031-0182(02)00480-7

Chen, G., Dalton, C., & Taylor, D. (2010). Cladocera as indicators of trophic state in Irish lakes. *Journal of Paleolimnology*, *44*(2), 465-481. https://doi.org/10.1007/s10933-010-9428-2

Davidson, T. A., Sayer, C. D., Perrow, M., Bramm, M., & Jeppesen, E. (2010). The simultaneous inference of zooplanktivorous fish and macrophyte density from sub-fossil cladoceran assemblages: A multivariate regression tree approach. *Freshwater Biology*, *55*(3), 546-564. https://doi.org/10.1111/j.1365-2427.2008.02124.x

Denys, L. (1991). A check-list of the diatoms in the Holocene deposits of the Western Belgian coastal plain with survey of their apparent ecological requirements. *Belgium: Ministerie van Economische Zaken.*

Faustová, M., Sacherová, V., Svensson, J. E., & Taylor, D. J. (2011). Radiation of European Eubosmina (Cladocera) from Bosmina (E.) longispina – Concordance of multipopulation molecular data with paleolimnology. *Limnology and Oceanography*, *56*(2), 440-450. https://doi.org/10.4319/lo.2011.56.2.0440

Frey, D. G. (1986). Cladocera analysis. In *Handbook of Holocene Palaeoecology and Palaeohydrology* (pp. 667-692). Chichester, UK: Wiley & Sons.

Frey, D. G. (1988). Littoral and offshore communities of diatoms, cladocerans and dipterous larvae, and their interpretation in paleolimnology. *Journal of Paleolimnology*, *1*(3). https://doi.org/10.1007/BF00177764

Gibbs, R. J. (1970). Mechanism controlling world water chemistry Sciences. *Science*, *170*(3962), 1088-1090. https://doi.org/10.1126/science.170.3962.1088

Guiry, M. D., & Guiry, G. M. (2022). *AlgaeBase*. Retrieved from http://www.algaebase.org

Heggen, M. P., Birks, H. H., Heiri, O., Grytnes, J. A., & Birks, H. J. B. (2012). Are fossil assemblages in a single sediment core from a small lake representative of total deposition of mite, chironomid, and plant macrofossil remains?. *Journal of Paleolimnology*, *48*(4), 669-691. https://doi.org/10.1007/s10933-012-9637-y

Hernández-Almeida, I., Grosjean, M., Gómez-Navarro, J. J., Larocque-Tobler, I., Bonk, A., Enters, D., Ustrzycka, A., Piotrowska, N., Przybylak, R., Wacnik, A., Witak, M., Tylmann, W. (2017). Resilience, rapid transitions and regime shifts: Fingerprinting the responses of Lake Żabińskie (NE Poland) to climate variability and human disturbance since AD 1000. *Holocene*, *27*(2). https://doi.org/10.1177/0959683616658529

Hoffmann, G. M., Werum, M., & Lange-Bertalot, H. (2011). *Diatomen im Süßwasser-Benthos von Mitteleuropa. Bestimmungsflora Kieselagen für die ökologishe Praxis. Über 700 der häufigsten Arten un ihre kologie*. A.R.G. Ganter Verlag K.G., Ruggell.

Jańczak, J. (1999). *Atlas Jezior Polski. Tom III Jeziora Pojezierza Mazurskiego i Polski południowej (The Atlas of Polish Lakes, vol. 3 Masurian Lakes and the Southern Part of Poland)*. Poznań: Bogucki Wydawnictwo Naukowe.

Jasiewicz, J., Zawiska, I., Rzodkiewicz, M., & Woszczyk, M. (2022). Interpretative machine learning as a key in recognizing the variability of lakes trophy patterns. *Quaestiones Geographicae*, *41*(1), 127-146. https://doi.org/doi.org/10.2478/quageo-2022-0009

Jekatierynczuk-Rudczyk, E., Zieliński, P., Grabowska, M., Ejsmont-Karabin, J., Karpowicz, M., & Więcko, A. (2014). The trophic status of Suwałki Landscape Park lakes based on selected parameters (NE Poland). *Environmental Monitoring and Assessment*, *186*(8), 5101-5121. https://doi.org/10.1007/s10661-014-3763-0

Juggins, S. (2007). *C2 Software for ecological and palaeoecological data analysis and visualisation. User guide. Version 1.5*. Newcastle upon Tyne, UK: Newcastle University.

Juggins, S., & Telford, R. J. (2012). Exploratory data analysis and display. In H. J. B. Birks, A. F. Lotter, S. Juggins, & J. P. Smol (Eds.), *Tracking environmental change using lake sediments: Data handling and statistical techniques* (pp. 123-142). Dordrecht: Springer.

Kalff, J. (2002). *Limnology – Inland Water System*. New Jersey: Prentice Hall.

Kawecka, B., & Eloranta, P. V. (1994). *Zarys ekologii glonów wód słodkich i środowisk lądowych.* Warszawa: Wydawnictwo Naukowe PWN.

Kirilova, E. P., Heiri, O., Bluszcz, P., Zolitschka, B., & Lotter, A. F. (2011). Climate-driven shifts in diatom assemblages recorded in annually laminated sediments of Sacrower See (NE Germany). *Aquatic Sciences*, *73*(2), 201-210. https://doi.org/10.1007/s00027-010-0169-0

Kondracki, J. (2013). *Geografia regionalna Polski. Wydanie trzecie uzupełnione*. Kraków: Wydawnictwo Naukowe PWN.

Korhola, A., & Rautio, M. (2001). Cladocera and other Branchiopod Crustaceans. In J. P. Smol, H. J. B. Birks, & W. M. Last (Eds.), *Tracking environmental change using lake sediments. Vol. 4, Zoological Indicators* (pp. 5-41). Springer Netherlands.

Kotrys, B., Płóciennik, M., Sydor, P., & Brooks, S. J. (2020). Expanding the Swiss-Norwegian chironomid training set with Polish data. *Boreas*, *49*(1), 89-107. https://doi.org/10.1111/bor.12406

Krammer, K., & Lange-Bertalot, H. (2008a). Bacillariophyceae 2, Ephitemiaceae, Bacillariaceae, Surirellaceae. In H. Ettl, J. Gerloff, H. Heyning, & D. Mollenhauer (Eds.), *Süsswasserflora von Mitteleuropa 2. T 2, Fourth edition* (p. 596). Stuttgardt: Fisher.

Krammer, K., & Lange-Bertalot, H. (2008b). Bacillariophyceae 3, Centrales, Fragilariaceae, Eunotiaceae. In H. Ettl, J. Gerloff, H. Heyning, & D. Mollenhauer (Eds.), *Süsswasserflora von Mitteleuropa 2. T 3, Third edition* (p. 577). Stuttgardt: Fisher.

Krammer, K., & Lange-Bertalot, H. (2010). Bacillariophyceae 1. Naviculaceae. In H. Ettl, J. Gerloff, H. Heyning, & D. Mollenhauer (Eds.), *Süsswasserflora von Mitteleuropa 2. T 1, Fourth edition* (p. 876). Stuttgardt: Fisher.

Krammer, K., & Lange-Bertalot, H. (2011). Bacillariophyceae 4, Achnanthaceae. In H. Ettl, G. Gärtner, J. Gerloff, H. Heyning, & D. Mollenhauer (Eds.), *Süsswasserflora von Mitteleuropa 2. T 4, Third edition* (p. 437). Stuttgardt: Fisher.

Kuczyńska-Kippen, N. (2020). Biodiversity of zooplankton in Polish small water bodies. In E. Korzeniewska & M. Harnisz (Eds.), *Polish River Basins and Lakes – Part II Biological Status and Water Management* (pp. 55-76). Springer International Publishing. https://doi.org/10.1007/978-3-030-12139-6_3

Kurek, J., Korosi, J. B., Jeziorski, A., & Smol, J. P. (2010). Establishing reliable minimum count sizes for cladoceran subfossils sampled from lake sediments. *Journal of Paleolimnology*, *44*(2), 603-612. https://doi.org/10.1007/s10933-010-9440-6

Lamentowicz, M., Milecka, K., Gałka, M., Cedro, A., Pawlyta, J., Piotrowska, N., ... & van der Knaap, W. O. (2009). Climate and human induced hydrological change since AD 800 in an ombrotrophic mire in Pomerania (N Poland) tracked by testate amoebae, macro-fossils, pollen and tree rings of pine. *Boreas*, *38*(2), 214-229. https://doi.org/10.1111/j.1502-3885.2008.00047.x

Lange-Bertalot, H., Bąk, M., Witkowski, A., & Tagliaventi, N. (2011). Eunotia and related genera. In *Diatoms of Europe 6* (pp. 1-747).

Lange-Bertalot, H., & Genkal, S. I. (1999). Diatoms from Siberia I. Island in the Arctic Ocean (Yugorsky Shar Strait). In H. Lange-Bertalot (Ed.), *Iconographia Diatomologica: Annotated Diatom Micrographs, Vol. 6* (p. 294). Koeltz Scientific Books.

Lange-Bertalot, H., & Metzeltin, D. (1996). Indicators of Oligotrophy. 800 taxa representative of three ecologically distinct lake types. In H. Lange-Bertalot (Ed.), *Iconographia Diatomologica: Annotated Diatom Micrographs, Vol. 2* (p. 390).

Larocque-Tobler, I., Filipiak, J., Tylmann, W., & Bonk, A. (2015). Comparison between chironomid-inferred mean-August temperature from varved Lake Żabińskie (Poland) and instrumental data since 1896 AD. *Quaternary Science Reviews*, *111*, 35-50. https://doi.org/10.1016/j.quascirev.2015.01.001

Lauterbach, S., Brauer, A., Andersen,N., Danielopol, D. L.,Dulski, P., Hüls, M.,Milecka, K., Namiotko, T., Plessen, B., von Grafenstein, U. & Participants, D. (2011). Multi-proxy evidence for early to mid-Holocene environmental and climatic changes in northeastern Poland. *Boreas*, *40*, 57-72. https://doi.org/10.1111/j.1502-3885.2010.00159.x

Lotter, A. F., Birks, H. J. B., Hofmann, W., & Marchetto, A. (1998). Modern diatom, cladocera, chironomid, and chrysophyte cyst assemblages as quantitative indicators for the reconstruction of past environmental conditions in the Alps. II. Nutrients. *Journal of Paleolimnology*, *19*(4), 443-463. https://doi.org/10.1023/A:1007994206432

Luoto, T. P., Nevalainen, L., & Sarmaja-Korjonen, K. (2013). Zooplankton (Cladocera) in assessments of biologic integrity and reference conditions: application of sedimentary assemblages from shallow boreal lakes. *Hydrobiologia*, *707*(1), 173-185. https://doi.org/10.1007/s10750-012-1422-4

Marks, L. (2012). Timing of the Late Vistulian (Weichselian) glacial phases in Poland. *Quaternary Science Reviews*, *44*, 81-88.

Marszelewski, W. (2005). *Zmiany warunków abiotycznych w jeziorach Polski północno-wschodniej*. Toruń: Wydawnictwo Naukowe Uniwersytetu Mikołaja Kopernika.

Nevalainen, L., Luoto, T. P., Kultti, S., & Sarmaja-Korjonen, K. (2013). Spatio-temporal distribution of sedimentary Cladocera (Crustacea: Branchiopoda) in relation to climate. *Journal of Biogeography*, *40*(8), 1548-1559. https://doi.org/10.1111/jbi.12101

OECD. (1982). *Eutrophication of Waters. Monitoring, Assessment and Control., Final Report of the OECD Cooperative Programme on Monitoring of Inland Waters (Eutrophication Control), Organization for Economic Cooperation and Development, Paris,* 156.

Pochocka-Szwarc, K. (2010). Zapis glacilimnicznej sedymentacji w basenie Niecki Skaliskiej – północna część Pojezierza Mazurskiego. *Przegląd Geologiczny*, *58*(10), 1014-1022.

Pochocka-Szwarc, K. (2013). Some aspects of the last glaciation in the Mazury Lake District (north-eastern Poland). *Acta Palaeobotanica*, *53*(1), 3-8. https://doi.org/10.2478/acpa-2013-0001

Rydberg, J., Cooke, C. A., Tolu, J., Wolfe, A. P. & Vinebrook, R. D. (2020). An assessment of chlorophyll preservation in lake sediments using multiple analytical techniques applied to the annually laminated lake sediments of Nylandssjön. *Journal of Paleolimnology, 64*, 379-388. https://doi.org/10.1007/s10933-020-00143-z

Ralska-Jasiewiczowa, M., Demske, D. & van Geel, B. (1998). Holocene regional vegetation history recorded in the Lake Gościąż sediments. In Ralska-Jasiewiczowa, M., Goslar, T., Madeyska, T. & Starkel, L. (Eds): *Lake Gościąż, Central Poland. A monographic study* (pp. 202-219). Kraków: W. Szafer Institute of Botany, Polish Academy of Sciences.

Rzodkiewicz, M. (2018). *Wykorzystanie współczesnych zespołów okrzemkowych w rekonstrukcjach paleośrodowisk jezior przybrzeżnych*. Poznań: Bogucki Wydawnictwo Naukowe.

Scofield, A. E., Watkins, J. M., Osantowski, E., & Rudstam, L. G. (2020). Deep chlorophyll maxima across a trophic state gradient: A case study in the Laurentian Great Lakes. *Limnology and Oceanography*, *65*(10), 2460-2484. https://doi.org/10.1002/lno.11464

Schubert, C. J., Lucas, F. S., Durisch-Kaiser, E., Stierli, R., Diem, T., Scheidegger, O., Vazquez, F. & Müller, B. (2010). Oxidation and emission of methane in a monomictic lake (Rotsee, Switzerland). *Aquatic Sciences, 72,* 455-466. https://doi.org/10.1007/s00027-010-0148-5

Sienkiewicz, E., & Gąsiorowski, M. (2017). The diatom-inferred pH reconstructions for a naturally neutralized pit lake in south-west Poland using the Mining and the Combined pH training sets. *Science of the Total Environment*, *605-606*, 75-87. https://doi.org/10.1016/j.scitotenv.2017.06.171

Sienkiewicz, E., Gąsiorowski, M., Hamerlík, L., Bitušík, P., & Stańczak, J. (2021). A new diatom training set for the reconstruction of past water pH in the Tatra Mountain lakes. *Journal of Paleolimnology*, *65*(4), 445-459. https://doi.org/10.1007/s10933-021-00182-0

Szeroczyńska, K., & Sarmaja-Korjonen, K. (2007). *Atlas of Subfossil Cladocera from Central and Northern Europe*. Friends of the Lower Vistula Society.

Tylmann, W., Szpakowska, K., Ohlendorf, C., Woszczyk, M., & Zolitschka, B. (2012). Conditions for deposition of annually laminated sediments in small meromictic lakes: A case study of Lake Suminko (northern Poland). *Journal of Paleolimnology*, *47*(1), 55-70. https://doi.org/10.1007/s10933-011-9548-3

Wetzel, R. G. (2001). *Limnology. Third Edition*. Elsevier.

Wilkinson, G. M., Cole, J. J., Pace, M. L., Johnson, R. A., & Kleinhans, M. J. (2015). Physical and biological contributions to metalimnetic oxygen maxima in lakes. *Limnology and Oceanography*, *60*(1), 242-251. https://doi.org/10.1002/lno.10022

Witak, M., Hernández-Almeida, I., Grosjean, M., & Tylmann, W. (2017). Diatom-based reconstruction of trophic status changes recorded in varved sediments of Lake Żabińskie (northeastern Poland), AD 1888-2010. *Oceanological and Hydrobiological Studies*, *46*(1), 1-17. https://doi.org/10.1515/ohs-2017-0001

Witkowski, A., Cedro, B., Kierzek, A., & Baranowski, D. (2009). Diatoms as a proxy in reconstructing the Holocene environmental changes in the south-western Baltic Sea: the lower Rega River Valley sedimentary record. *Hydrobiologia*, *631*(1), 155-172. https://doi.org/10.1007/s10750-009-9808-7

Zawiska, I., Apolinarska, K., & Woszczyk, M. (2019). Holocene climate vs. catchment forcing on a shallow, eutrophic lake in eastern Poland. *Boreas, 48*(1), 166-178. https://doi.org/10.1111/bor.12347

Zawiska, I., Słowiński, M., Correa-Metrio, A., Obremska, M., Luoto, T., Nevalainen, L., Milecka, K. (2015). The response of a shallow lake and its catchment to Late Glacial climate changes – A case study from eastern Poland. *Catena*, *126*, 1-10. https://doi.org/10.1016/j.catena.2014.10.007

Zawisza, E., Zawiska, I., & Correa-Metrio, A. (2016). Cladocera community composition as a function of physicochemical and morphological parameters of dystrophic lakes in NE Poland. *Wetlands*, *36*(6), 1131-1142. https://doi.org/10.1007/s13157-016-0832-x

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