The recent deposition of laminated sediments in highly eutrophic Lake Kierskie, western Poland: 1 year pilot study of limnological monitoring and sediment traps

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Abstract Accurate lake sediment-derived palaeoenvironmental reconstructions require in-depth knowledge on sediment record formation processes. In order to understand formation of laminated sediments in the eutrophic Lake Kierskie (western Poland) we conducted a year-round (November 2015–October 2016), monthly sediment trap study along with physico-chemical water properties, water transparency, hardness, alkalinity, nutrients and solute content, trophic state indices, and the phytoplankton assemblage monitoring. Sedimentation in Lake Kierskie primarily resulted from the activity of photosynthetic organisms. The maxima of biogenic silica accumulation were synchronous with the bloom of centric diatoms observed in March and April. These were followed by the most intensive precipitation of CaCO_3 noted

between mid-April and mid-June, that corroborated with the domination of *Stephanodiscus hantzschii* and small flagellate forms acting as nucleation sites for crystal formation. At the same time shift from the diatom-dominated assemblages to the communities composed of chlorophytes, cryptophytes, and dinoflagellates, the groups with cellulose external covering, resulted in decreased proportion between SiO_2 and organic matter. CaCO_3 precipitation continued in the summer months, however its amount decreased simultaneously with a drop in *S. hantzschii* biomass. The significant overall flux of biogenically mediated materials from epilimnion was promoted by eutrophic towards hypertrophic conditions in Lake Kierskie revealed by the trophic state indices. Mixing of the water column in autumn triggered resuspension and redeposition of the previously deposited sediments resulting in the second, after the early spring, maximum sediment flux. Minima of sediment accumulation were observed during the winter water stratification

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when the smallest particles sedimented from suspension. The sediment flux to the lake bottom recorded by us in a 1-year, monthly sediment trap study matches a sequence of pale, whitish lamina deposited during spring and summer, followed by dark, grayish or black lamina deposited in the autumn and winter, observed in the macroscopic investigation of the short (0.5 m) core from Lake Kierskie. Preservation of distinct laminations in the dimictic Lake Kierskie is supported by anoxic hypolimnion developed under the high supply of organic matter from epilimnion of this highly eutrophic lake.

Keywords Laminated sediments · Sediment trap study · Hypertrophic lake · Primary productivity · Calcite precipitation

Introduction

Varves are a specific type of lacustrine sediments composed of repetitive succession of laminae, and sedimentologically are regarded as rhythmites. A needed precondition for varve formation is the seasonally variable flux of material to the lake bottom derived from autochthonous and/or allochthonous sources (Zolitschka et al. 2015). Depending on varve composition, and processes leading to their formation, clastic, endogenic and biogenic varves are distinguished (Zolitschka et al. 2015). The genesis of clastic varves is related to seasonally variable flux of detrital material from lake catchment during periods of increased runoff, e.g. seasonally increased precipitation (Corella et al. 2012) or seasonal glacier melting (Ojala et al. 2013). Formation of endogenic varves is related to seasonally variable flux of minerals precipitated chemically in the water column, however not related to living organisms (Neugebauer et al. 2014). Rhythmic character in biologically mediated laminated sediments formed in lakes, commonly referred to as biogenic varves, depends on the seasonally variable flux of material related directly or indirectly to the activity of primary producers. Primary producers are responsible for the origin of the three major geochemical components of the sediments in the pelagial parts of deep lakes, i.e. organic matter, biogenic silica and biogenically precipitated carbonates (Bonk et al. 2015). When the seasonal flux of

material to the lake bottom depends on a combination of two or three of the above-mentioned processes varves of intermediate character are formed, e.g. the clastic-biogenic varves described by Ojala et al. (2013).

Although seasonally variable flux of material to the lake bottom is typical for many lakes, only some preserve the seasonally specific sequence of laminae. Preservation of the varves is usually disturbed by postsedimentary processes, including ebullition of gasses from the sediments, water currents or activity of benthic organisms (Tylmann et al. 2012). Therefore, laminated sediments are found primarily in the deep parts of well-stratified lakes, sheltered from wind action, with an anoxic bottom that prevents the presence of benthic fauna (Ojala et al. 2000). The detailed discussion of the favourable conditions for the preservation of annually laminated sediments was presented by Zolitschka et al. (2015).

Like other lake deposits, varves are sensitive recorders of environmental changes. However, in contrast to massive lacustrine sediments they preserve high resolution, annual or even seasonal data on within-lake processes (water mixing regime, productivity), and transformations of the lake catchment (land-use change, change in precipitation patterns) (Ralska-Jasiewiczowa et al. 2003; Amann et al. 2014; Czymzik et al. 2016; Poraj-Górska et al. 2017; Źarczyński et al. 2019). Among the different types, biogenic varves are highly valued as one of the best archives on land with documented applicability in palaeoenvironmental reconstructions (Zolitschka et al. 2000; Ojala and Alenius 2005; Tylmann et al. 2013).

Many of the biogenic varved records studied, of late glacial and early Holocene age in particular, were formed with no or minimal interference by human activity and are a result of natural processes (Goslar et al. 1999; Lücke et al. 2003; Chu et al. 2005). However, varved sediments have also been reported from anthropogenically influenced lakes (Kienel et al. 2013; Poraj-Górska et al. 2018; Źarczyński et al. 2019). Distinguishing between the natural and human-related genesis of laminated lake sediments has already been documented (Enters et al. 2010; Vegas-Vilarrúbia et al. 2018; Kinder et al. 2019). The key factor responsible for establishing of the laminated sediments in the lakes located in the areas inhabited by humans is increasing deep water hypoxia or even

anoxia (Jenny et al. 2016a, b), commonly related to lake eutrophication. Although the influence of men on lakes (e.g., deforestation of lakes catchments) has been noted at least since the time humans started to cultivate the land, its significance and scale have increased in modern times (Enters et al. 2008). Wastes supplied to lakes by industries, dense human settlements, and application of fertilizers by farmers, resulted in water pollution, and commonly observed lake eutrophication (Wetzel 2001; Smith 2003; Smith and Schindler 2009). By analyzing the temporal trends of lacustrine hypoxia onset over the past 300 years Jenny et al. (2016a) have demonstrated that the start and intensification of lacustrine hypoxia were strongly related to widespread urbanization and enhanced P discharges from urban point sources. Enhanced primary productivity and increased sediment flux from epilimnion linked e.g. with algal blooms, can create anoxic conditions that hamper sediment bioturbation and allow rhythmical sediment deposition (Jenny et al. 2016a). The presence of annually laminated sediments recently has become an indicator used to assess the long-term dynamics of hypoxia in lakes (Jenny et al. 2016b).

High-resolution studies of the biogenic varve records aiming to reconstruct both, natural and human-related environmental conditions during the varves formation, rely on detailed characteristics of the laminae (Martin-Puertas et al. 2012; Bonk et al. 2016; Tylmann et al. 2017). Such studies require an in-depth understanding of processes leading to varves formation. This might be achieved only by a combination of comprehensive monitoring and sediment trap study. On the one hand, the monitoring study should include cyclic measurements of physico-chemical water properties to provide the background for sediment formation. Moreover, phytoplankton assemblages, as well as trophic state indices, should be well recognized, since major sediment components of biogenic varves are highly dependent on the lake primary productivity (Brauer 2004). The sediment trap studies, in turn, give an insight into seasonality in the amount and geochemical composition of the sediment flux to the lake bottom (Flower 1991; Tylmann et al. 2012; Bonk et al. 2015). As a result, the combined monitoring of the within-lake conditions and sediment trap studies allow for a direct comparison of the final characteristic of the sediments and water conditions during their formation. Installation of the sediment

traps at different water depths allows to track the fate of the particles settling down within the water column (Bluszcz et al. 2009), which may be subjected to dissolution (calcite) and decomposition (organic matter) as they sink from the epilimnion to the physico-chemically different hypolimnion (Ramisch et al. 1999). In addition, sediment traps installed at different water depths are of fundamental importance for understanding the role of sediment resuspension and focusing (Charlton and Lean 1987; Bloesch 1994; Evans 1994) on varves formation.

The present study aims to recognize conditions of recent sedimentation of laminated sediments in highly eutrophic Lake Kierskie (western Poland, central Europe) applying comprehensive monitoring of the water characteristics and trophic state along with sediment trap studies. Lake Kierskie was chosen for a study based on the laminated character of its sediments. Laminations are present along most of the 14-m-long core, however, their record is discontinuous; laminated sediments are intercalated with massive, homogenous sediments. The youngest, well-preserved lamination, a record of most recent sedimentation, extends approximately 0.5 m below the lake bottom. It is hypothesized that sediment formation and composition in the studied lake are controlled by primary productivity. Intense phytoplankton blooms contributing to the biogenic silica deposition, and biologically mediated heavy CaCO_3 precipitation, are expected to be variable seasonally. Biological production and therefore also sediment formation in Lake Kierskie are believed to be enhanced by high fertility of the lake, which has increased greatly in the second half of the twentieth century in response to increased residential and built-up areas and the establishment of recreational infrastructure. Findings of this study will be helpful in the downcore analysis of laminated sediments in Lake Kierskie but are expected to be of value in the studies of other biogenic varved sediments that aim to reconstruct eutrophication impact on lake ecosystem in a temporal scale beyond instrumental record.

Study site

Lake Kierskie is located in the Poznań Lake District (western Poland) in the north-western periphery of the city of Poznań (52° 27' N; 16° 47') at 72 m asl (Fig. 1a, b). It was formed during the recession of the

Weichselian ice sheet that left the area around 18.5 ka BP (Kozarski 1995). Morphology of the 70.6 km² catchment of the lake is dominated by flat and undulating upland as well as by low laying former glacial tunnel valley within which basin of the lake is located. The surface sediments of the area consist predominantly of Pleistocene glacial till and glaciofluvial deposits. The climate of this region is transitional, between the mild and humid Atlantic climate of Western Europe and the East European continental climate. The mean annual air temperature is 8 °C, with monthly averages between −2.2 °C in January and 18 °C in July (Woś 1994). Annual precipitation varied between 1981 and 2015 from 275 to 715 mm (Szyga-Pluta and Grześkowiak 2016).

Lake Kierskie is elongated in a northwest-southeast direction and covers an area of 2.86 km². It is subdivided into deeper (maximum depth 35 m) southern basin and shallower (maximum depth 20 m) northern basin (Fig. 1d). The deepest part of the lake is characterized by the steep (up to ~ 14°) slopes. The

exposure index (ratio between the lake surface area and mean depth; Tylmann et al. 2013) is relatively low (28.3) pointing to good protection of the deep waters from wind-induced mixing. Such morphometric parameters favoured deposition of laminated sediments in the southern basin of the lake (Fig. 3). The lake is fed by several inflows and is drained by the single outflow located on its north-eastern end (Fig. 1d). Kowalczak and Sosiński (1995) assessed a groundwater inflow to contribute significantly to an overall water input to the lake. Mean water residence time is 25–33 years (Jańczak and Sziwa 1995).

The catchment of the lake is presently dominated by cultivated lands and meadows (Fig. 1c). The forested area is limited mainly to a zone adjacent to the eastern shores of the lake, while built-up areas are scattered within the catchment. Both cultivated and urbanized areas are drained by the lake's inflows what significantly enhance nutrient supply to the lake. Average concentrations of total nitrogen (TN) and total phosphorus (TP) in four major inflows supplying

Fig. 1 Location of Lake Kierskie in Europe (a) and Poland (b). Land use of Lake Kierskie catchment with the main drainage network (c). Bathymetric map of Lake Kierskie with the location of the sediment traps marked with a white dot (d)

Lake Kierskie, measured monthly between June and October 2016, ranged between 2.79–6.71, and 0.12–0.87 mg l⁻¹, respectively (Grzonka et al. 2016). In the southern part of the lake, where the study was carried out the loadings of nutrients in the inflows were at the lower end of the values measured, TN values were even at 3.6 mg l⁻¹, whereas TP values ranged between 0.12 and 0.18 mg l⁻¹. Considering the biogenic compounds loading of the main tributary of the lake, the Samica Kierska River, inflowing into Lake Kierskie from NW (TN 6.71 mg l⁻¹ and TP 0.87 mg l⁻¹) and discharging the lake in NE (TN 1.75 mg l⁻¹ and TP 0.05 mg l⁻¹), Lake Kierskie is a sink of the nutrients supplied from its catchment. In addition to nutrient loads by inflows, the lake is commonly used for recreational purposes and several beaches and resorts are placed on its shores. In reaction to the alarmingly increasing trophy of waters in Lake Kierskie, since 1988, actions have been undertaken to restore the lake. In order to decrease eutrophication of lake waters and reduce phosphorus release from lake sediments under hypoxic/anoxic conditions occurring during winter and summer stratification of the lake, five aerators were installed (<http://www.swkiekrz.pl/>), two in the northern part of the lake and three in its southern, deepest part. The aerators are sucking in waters from the hypolimnion at the depth of about 30 meters and transport them to the lake surface. During the summer stratification, the aerators additionally transport the oxygenated waters down from the surface and release them at the depth of about 14 meters. Similar restoration programs aiming to reduce the extent of lake eutrophication and deep waters hypoxia have been carried out since the 1970s in many European and North-American lakes (Jenny et al. 2016b) (Fig. 2).

Materials and methods

Field studies

To recognize the conditions of laminated sediments deposition in Lake Kierskie monitoring study of the water characteristics and the trophic state was carried out in roughly monthly intervals between November 2015 and October 2016, at the deepest part of the lake (35 m; GPS: N 52° 26' 53.7" E 16° 47' 49.8"). The following parameters were measured directly at the

Fig. 2 Early Holocene (a) and modern (b) laminated sediments from Lake Kierskie. In the sediment sequence from Lake Kierskie (14 m long) laminated sediments occur discontinuously and are usually poorly formed. Continuous laminated sediments were observed in the Early Holocene (they are approximately 1.9 m thick and start at the bottom of the sediment sequence) and in the uppermost part of the sediment sequence (approximately 0.5 m). The study concentrates on conditions of formation of the most recent laminated sediments

study site: water transparency was estimated by Secchi disk, and, temperature, dissolved oxygen concentration, electrolytic conductivity, and pH were measured in the vertical profile at 1-m intervals to a depth of 30 m, using YSI Professional Plus, Yellow Springs, Ohio, USA. The samples for analyses of ionic concentration in waters and concentration of chlorophyll-*a* were collected with a 5-l water sampler (bathometer, Uwitec Plexiglas Watersampler, Mondsee, Austria) at the depths of 1, 16 and 30 m, and poured into 1.5 and 1-l plastic bottles, respectively. Samples for algological analyses (qualitative and quantitative structure of phytoplankton) were collected from the same depths, poured into 1-l plastic bottles and preserved using Lugol's solution. The depths of 1, 16 and 30 m were chosen to recognize the epilimnion, metalimnion/shallow hypolimnion, and hypolimnion (above bottom) limnological conditions. Recognition of the geochemical and elemental characteristics of the material sedimented in the water

column during the monitoring study was carried out applying a sediment trap study. Installation of the sediment traps at 16 (two PCV tubes) and 30 m (four PCV tubes) of water depth (Fig. 3) allowed to track the fate of the particles sedimenting within the water column. Sediments were collected from plastic caps mounted at the lower ending of 1 m long, 0.06 m in diameter PCV tubes. All the samples, both water, and sediments were kept in a refrigerator until further laboratory analyses were performed.

In order to determine the onset of deposition of recent laminated sediments in Lake Kierskie a short sediment core was collected (Fig. 2) with the Uwitec gravitational corer (1 m long and 0.04 m in diameter) in September 2018, from the same place where the preceding sediment trap study was carried out.

Laboratory work

Water samples

Concentrations of PO_4^{3-} and Ca^{2+} in the water samples were determined using the 881 Compact IC

Fig. 3 Sketch presenting the construction of the sediment traps installed in Lake Kierskie. The detailed description is presented in the text

Pro model Metrohm ion chromatograph (Metrohm, Switzerland). Details of the analytical procedures applied were presented elsewhere (Pelechaty et al. 2010). Determination of total alkalinity was performed by titration of a 0.1 mol l^{-1} HCl-acidified water sample against methyl orange as an indicator. The bicarbonate concentration was calculated by multiplying the alkalinity results by 61 g mol^{-1} (the molar mass of HCO_3^-). pH and alkalinity measurements were used to calculate the CO_3^{2-} concentration (Stumm and Morgan 1981). Total water hardness was determined using the versenate method.

Calcite saturation Index (SI) was calculated using an online calculator (<https://www.lenntech.com/calculators/langelier/index/langelier.htm>), according to the equation:

$$\text{SI} = \text{pH} - \text{pH}_s,$$

where pH is the pH value of lake waters and pH_s —is the pH of lake waters saturated with calcium (calculated on the basis of water temperature, conductivity, Ca^{2+} , and HCO_3^- concentrations).

Water samples for phytoplankton analyses were decanted, condensed to a volume of 10 ml and then preserved with formaldehyde. Qualitative (number of taxa and species composition) and quantitative (abundance, taken as the number of individuals per ml, and biomass) analyses of phytoplankton were performed using a Leica DMLB microscope (Leica Microsystems, Wetzlar, Germany). Phytoplankton individuals were counted in 100 fields of a Fuchs-Rosenthal counting chamber (height: 0.2 mm, area: 0.0625 mm^2). Phytoplankton biomass was estimated by calculating species biovolume following the criteria and formulae proposed by Wetzel and Likens (2001). As an additional measure of phytoplankton productivity, the concentration of chlorophyll-*a* was determined spectrophotometrically (model SP-830 Plus, Metertech, Taipei, Taiwan) after water sample filtration on Whatman GF-C glass-fibre filters, grinding of the filters using a mortar and 24 h extraction in 90% acetone. Based on the determined summer (June–August) chlorophyll-*a* concentrations and Secchi disc transparency the Carlson's (1977) Trophic State Index (TSI) was calculated as $\text{TSI}(\text{Chla})$ and $\text{TSI}(\text{SD})$, following the respective formulas:

$$\text{TSI(Chl)} = 10 \left(6 - \frac{2.04 - 0.68 \ln \text{Chl}}{\ln 2} \right)$$

$$\text{TSI(SD)} = 10 \left(6 - \frac{\ln \text{SD}}{\ln 2} \right)$$

$$\text{TSI} = \left(\frac{\text{TSI(Chl)} + \text{TSI(SD)}}{2} \right)$$

Since the bioavailable concentrations of PO_4^{3-} were determined, not the total phosphorus, the TSI(TP) was not included, TSI values < 40 indicate oligotrophic conditions in a given lake, while the TSI values exceeding 50 characterize eutrophic conditions. TSI values 40–50 are typical of mesotrophic lakes.

Sediment samples

A tiny portion of fresh sediments collected from sediment traps were used for smear slide analysis. The preparation of the samples followed the Limnological Research Centre methods (<https://tmi.laccore.umn.edu/>). Remaining sediments from the traps were placed in the previously weighted (RADWAG WAA 62/X/1, 0.0001 g, RADWAG, Radom, Poland) glass evaporating dishes and dried at 40 °C. The total sediment weight of each of the sample (bulk sediment) was determined as a difference between an evaporating dish with the dried sediment and an empty evaporating dish. Prior to geochemical analysis sediments collected in the two PCV tubes at 16 m and four PCV tubes at 30 m were combined (separately for the two depths) in order to obtain one sample per depth. The content of total carbon (TC) was determined using VarioMax CNS elemental analyzer (Elementar, Langensfeld, Germany). Analysis of the total organic carbon (TOC) was carried out using the same analyzer after decalcification of the samples with 1 M HCl. Total inorganic carbon (TIC) was determined as a difference between TC and TOC. Each sample was analyzed in duplicate. Analytical control was performed with certified reference materials and the precision was $\pm 0.06\%$ for C content analysis. To determine the percentage content of calcium carbonate (CaCO_3) and organic matter (OM), TIC was multiplied by 8.33 (the ratio of mole masses of C and CaCO_3), and TOC was multiplied by 2.5 (the ratio of mole masses of C and CH_2O), respectively. The remaining material, regarded by us as dominated by

SiO_2 content was calculated as a difference between the total mass of the sample, CaCO_3 and OM contents. Such an approach involves simplification because it disregards some minor components of the sediment e.g. iron sulfides observed by us on the smear slides. However, this approach is further justified by a clear match between changes in the presence and abundance of diatoms and changes in the amount of residual material, regarded by us as SiO_2 . Also, the study site is distant from the inflows supplying the lake, and the main tributary the Samica Kierska River, is located in the northern basin of Lake Kierskie (Fig. 1), therefore, no significant source of minerogenic matter to the study site exists. Numerous studies of the biogenic varves showed that besides CaCO_3 and OM, SiO_2 is the third basic component of the sediments (Bonk et al. 2015; Zolitschka et al. 2015; Ott et al. 2018). According to Tylmann et al. (2013) in lakes of northeastern Poland input of minerogenic matter is of minor importance and catchment conditions play a secondary role in the formation of laminated sediments. However, the content of minerogenic matter in sediments depends strictly on local conditions and there may be lakes with significant minerogenic matter content in their sediments. The weight of bulk samples and the geochemical composition of the sediments accumulated in the traps was used to calculate mass accumulation rate ($\text{g m}^{-2} \text{day}^{-1}$) of bulk sediments, carbonates, organic matter, and total silica.

Counting of sediment laminae

The short core retrieved from the deepest part of Lake Kierskie (Fig. 2) was examined in the laboratory. To estimate the rough onset of deposition of the recent laminated sediments pairs of light and dark laminae were macroscopically counted assuming they were deposited in the yearly cycle. The counting was conducted by two investigators.

Results

The time extent of deposition of the recent laminated sediments

The macroscopic examination of the short sediment core retrieved from the deepest basin of Lake Kierskie allowed distinguishing approximately 45 pairs of

laminae, each pair consisting of light (whitish) and dark (grey to black) laminae (Fig. 2b). With increasing depth, the laminae became less distinct and gradually passed into massive sediments. Assuming the pair of laminae were deposited in a yearly cycle, the onset of laminated sediments formation might be roughly estimated to the early 1970 s. This date is concurrent with increased residential and built-up areas and establishing recreational infrastructure in the lake catchment at that time.

The main sediment components

The main components of the trapped sediments were recognized via the qualitative smear slide analysis. Authigenic calcite, commonly in the form of regular rhombohedra was shown to be the main source of carbonates, thus the CaCO_3 abundance might be interpreted mainly in terms of calcite precipitation and dissolution rates (Ramisch et al. 1999). Most of the crystals occurred in two class sizes. Calcite, as the mineral form of CaCO_3 precipitated, was proven by the Mg-to-Ca molar ratio below 0.3 in the epilimnion of Lake Kierskie (ESM 1). Organic matter was found to be generally brown and amorphous, similar to

described in smear slides analysis of sediment trap material from other lakes with varve sediments (e.g. Bonk et al. 2015). Origin of the organic matter was determined as primary productivity by C to N atomic ratio rarely exceeding 8 (ESM 1). The remaining components were dominated by biogenic silica building diatom frustules, which justifies our assumption that biogenic silica abundance can be regarded as a difference between the bulk sediment and sum of carbonates and organic matter. Among the accessory components, single pyrite crystals were found, several invertebrates remains (mainly copepods) and few siliciclastic grains.

Annual changes in physico-chemical parameters of water in Lake Kierskie, productivity and sediment flux to the lake bottom

Late autumn

In November 2015 lake water column was homogeneous for chemical and physical parameters (Fig. 4; ESM 1), indicating a mixing period. This situation lasted until December 2015. Mixing of the water column was also recorded in the low and similar

Fig. 4 Temporal changes in temperature, dissolved oxygen, pH and conductivity measured in 1 m intervals during the monitoring period. The break in the field studies during winter is marked in grey

concentration of chlorophyll-*a* ($0.59\text{--}3.3\ \mu\text{g l}^{-1}$; ESM 1) and phytoplankton assemblages occurring in the surface waters, at 16 and 30 m of the water depth

(ESM 2, Fig. 5). At each depth, the cryptophyte *Plagioselmis nannoplantica* (Skuja) Novarino, Lucas et Morrall was the dominant species in terms of

Fig. 5 Phytoplankton community studied in Lake Kierskie since November 2015 through October 2016: total biomass (a); total abundance (b); share of phytoplankton groups in the total biomass (c) and total abundance (d) in epilimnion; percentage share of dominant species in the total biomass (e) and total abundance (f) in epilimnion. *C. microp.*—*Coelastrum microporum* Nägeli, *L. verrucosa*—*Lobomonas verrucosa* Skuja, *P. nannopl.*—*Plagioselmis nannoplantica* (Skuja) Novarino, Lucas et Morrall, *C. curvata*—*Cryptomonas curvata* Ehrenberg, *C. hirundin.*—*Ceratium hirundinella* (O.F.Müller) Dujardin, *S. hantzschii*—*Stephanodiscus hantzschii* Grunow, *O. lacustris*—*Oocystis lacustris* Chodat, *B. braunii*—*Botryococcus braunii* Kützing, *C. marssonii*—*Cryptomonas marssonii* Skuja, *M. tenuiss.*—*Merismopedia tenuissima* Lemmermann, *C. parva*—*Chrysochromulina parva* Lackey, *M. dybowskii*—*Monoraphidium dybowskii* (Woloszynska) Hindák et Komárkova Legnerová, *A. gracile*—*Aphanizomenon gracile* (Lemmermann) Lemmermann

abundance while the diatom *Stephanodiscus hantzschii* Grunow dominated in terms of biomass. Water transparency in November and December (4 and 7.5 m, respectively; Fig. 6j) suggests low primary production. Simultaneously, bulk sediment flux to the

traps was among the highest in the study period (3.5 and $6.54 \text{ g m}^{-2} \text{ day}^{-1}$ at 16 and 30 m, respectively; Fig. 6a; ESM 1) and was dominated by CaCO_3 (2.1 and $4.0 \text{ g m}^{-2} \text{ day}^{-1}$ at 16 and 30 m, respectively; Fig. 6b; ESM 1).

Fig. 6 Sediment flux to the sediment traps during the monitoring period presented separately for the major geochemical components of the sediments, i.e. the bulk sediment sample (a), CaCO_3 (b), organic matter (c) and SiO_2 (d). Samples from traps installed at 16 and 30 m water depth are marked with different signatures. If not indicated differently, all the physico-chemical parameters (f–k) refer to the surface waters (1 m deep). The sample collected at 16 m in September was lost during the laboratory procedure. Temperature data from the meteorological station located at Ławica airport, approximately 3 km to the SE from Lake Kierskie, is shown along with the water temperature data (e)

Winter

Presence of the discontinuous ice cover on the lake disabled winter observations (Fig. 4). Deposits collected in the sediment traps during winter recorded the lowest sediment flux to the lake bottom during the period studied (1.04 and $1.48 \text{ g m}^{-2} \text{ day}^{-1}$ at 16 and 30 m, respectively; Fig. 6a; ESM 1). Calcium carbonates contributed most abundantly to the sediments (0.5 and $0.8 \text{ g m}^{-2} \text{ day}^{-1}$ at 16 and 30 m, respectively; Fig. 6b; ESM 1).

Spring and summer

Early spring water turnover in March is indicated by equalized values of temperature and oxygen concentration in the water column (Fig. 4). However, vertically variable values of pH and conductivity suggest that the mixing process was not complete and was active mainly in the upper 10 meters of the water column. Intensified primary productivity during the early spring is evidenced by increased chlorophyll-*a* ($35.1 \mu\text{g l}^{-1}$) concentrations (Fig. 6i). Assimilation of CO_2 and release of O_2 by primary producers resulted in increased pH values (7.9), and O_2 (14.3 mg l^{-1}) concentrations (Figs. 4, 6f). Water transparency decreased to 2.5 m (Fig. 6j). In the early spring, phytoplankton assemblage was dominated by centric diatoms (*S. hantzschii*, *Cyclotella* sp.) blooming at 1 m and 16 m while the deepest water layers were dominated by less abundant cyanobacteria (Fig. 5; ESM 2). With increased epilimnion temperatures in April water stratification was established (Fig. 4). The most intense, during the monitoring period, spring primary productivity, at concentration of PO_4^{3-} -phosphorus between 0.41 and 0.39 mg l^{-1} (Fig. 6k), resulted in increased surface water pH (8.9), higher O_2 and chlorophyll-*a* concentrations in the epilimnion (20.7 mg l^{-1} and $70.4 \mu\text{g l}^{-1}$, respectively; Figs. 4, 6i; ESM1) and sharply decreased water transparency (0.9 m). Small flagellates predominated in the surface waters whereas representatives of centric diatoms were still present in deeper waters, accompanied by dinoflagellates (Fig. 4; ESM 2). This was concurrent with a peak in the remaining material, likely SiO_2 flux to the sediment traps (2.6 and $3.6 \text{ g m}^{-2} \text{ day}^{-1}$ at 16 and 30 m, respectively; Fig. 6d; ESM 1). The most intense CaCO_3 precipitation in the epilimnion was observed

between 15th April and 16th June (between 4.7 and $5.7 \text{ g m}^{-2} \text{ day}^{-1}$; Fig. 6b) when the calcite SI was calculated as 0.71 (Fig. 6h). During the period of spring and summer stagnation a bloom of phytoplankton, observed in the surface waters, was formed by chlorophytes in June and by dinoflagellates in the subsequent months. The small haptophyte *Chrysochromulina parva* Lackey was the most numerous species in the surface water layer while *Ceratium hirundinella* (Müller) Dujardin dominated the biomass not only in the surface waters but also at greater depths (Fig. 4; ESM 2). Intense primary productivity decreased nutrient concentration in the epilimnion and sustained elevated pH values (8.6–8.7) in the surface waters (Figs. 4, 6k; ESM 1). Precipitation of CaCO_3 resulted in Ca^{2+} depletion in the epilimnion (from 62 to 57 mg l^{-1} ; Fig. 6g). Decomposition of the OM settling in the water column is reflected in decreased O_2 concentration (0 – 5 mg l^{-1}) and pH (7.1–7.7) in the hypolimnion (Fig. 4). Dissolution of CaCO_3 at greater depths is evidenced by negative calcite SI values (-0.32 to -0.86), increased conductivity (840 – $920 \mu\text{S cm}^{-1}$) and Ca^{2+} (71 – 80 mg l^{-1}) content in the hypolimnion (Figs. 4, 6g, h).

Late summer and early autumn

Enhanced productivity during late summer was recorded in the highest concentration of chlorophyll-*a* in surface waters ($87.2 \mu\text{g l}^{-1}$) and water transparency decreased to values observed in April (0.9 m; Fig. 6i). It coincided with the highest value of phytoplankton biomass exceeding 65 mg l^{-1} in the surface water layer, formed by the dinoflagellate *C. hirundinella* (Fig. 5, ESM 2). In terms of phytoplankton abundance filamentous blue-greens dominated at all studied depths. Continuous CaCO_3 precipitation in surface waters since spring (Fig. 6b) strongly decreased the Ca^{2+} concentration (57.2 mg l^{-1}) and conductivity (760 – $780 \mu\text{S cm}^{-1}$) in the epilimnion (Figs. 4, 6g). Simultaneously, calcite dissolution in the hypolimnion is reflected in increases in both parameters (76 mg l^{-1} and 910 – $920 \mu\text{S cm}^{-1}$, respectively). Decomposition of the organic matter supplied from the epilimnion led to progressive depletion of the lake waters in dissolved oxygen. In mid-September anoxic conditions persisted within most of the water column, i.e. between 4 m and the lake bottom (Fig. 4).

Trophic conditions in Lake Kierskie

Carlson's (1977) Trophic State Index values reflected both chlorophyll-*a* concentrations as well as Secchi disk visibility. The TSI values exceeded 50 and had a maximum value of 60.6, which along with high phosphate concentrations and abundant phytoplankton, indicated eutrophic lake waters during the summer season of 2016.

Discussion

Factors controlling the formation of laminated sediments in Lake Kierskie

During the monitoring period, physical and chemical characteristics of Lake Kierskie waters were interrelated with the primary productivity in the epilimnion, sediment production and the annual cycle of water mixing and stratification.

The late autumn

The sediment total mass flux to the sediment traps between 13th November and 18th December 2015 constituted more than 17% of the total mass of the sediment accumulated during the monitoring period (Table 1), and thus was one of the highest during the monitoring period (Fig. 6a). The biomass of phytoplankton measured on 13th November and 18th December was very low, sharply lower compared to further seasons of the monitoring study (Fig. 5; ESM 2), which is also reflected in the lowest chlorophyll-*a* concentrations and the best water transparency in the whole study period (Fig. 6i, j). Therefore, material accumulated in the traps during the late autumn cannot be explained by the sediment flux from the epilimnion related to phytoplankton activity. High CaCO_3 contribution to the sediment (approximately 60% of the total sediment flux; Table 1; Fig. 6b) contradicts the negative calcite SI values (between -0.67 and -1 at all depths; Fig. 6h), which indicate suitable conditions for calcite dissolution. Therefore, we suggest that sedimentation during the late autumn must have been controlled by the processes related to water turnover in the lake, the latter indicated by the vertically unified phytoplankton biomass and physico-chemical

parameters of the water (ESM 1; Fig. 4). In Lake Kierskie the processes of sediment resuspension activated by water movement during the lake turnover, and subsequent redeposition of the material are regarded as critical for the increased sediment flux during the late autumn. Sediment resuspension and redeposition are well known from lakes (Charlton and Lean 1987) and have been shown to result in a secondary flux of resettling material in sediment traps (Bloesch 1994; Evans 1994). The redeposited sediment is expected to form distinct laminae within the yearly sediment record in Lake Kierskie, however, this is still to be proven by microscopic study of laminated sediments. Preservation of the laminated sediments in the deepest part of the lake studied indicates that the resuspended material must have originated mostly from the shallower parts of the lake (Tylmann et al. 2012). Resuspension of the sediments from the deepest part of the lake was either absent or small enough to allow preservation of the seasonal flux in the sediments.

At the breakdown of water stratification in a lake an additional sediment flux may origin from the release of sediment particles trapped in the thermocline/chemocline, which then settle to the lake bottom and contribute to the sediment record (Punning et al. 2003; Rull et al. 2017). During the summer of 2016, the vertical profiles of both water temperature and conductivity in Lake Kierskie showed distinct shifts towards lower and higher values, respectively, at the depths of 6–10 m (Fig. 4). Such thermal and chemical gradients result in water density changes where some of the particles settle and can be released only after the gradients diminish or disappear as the water cools in the autumn and turnover of the water column establishes.

Focusing of the suspended material during the water turnover is indicated by a nearly double mass of the sediment accumulated in the sediment traps at 30 m, compared to the shallower traps (Fig. 6a; Table 1). Therefore, the actual sediment mass flux to the lake bottom can differ laterally and is expected to be greatest in the deepest part of the lake. Sediment focusing with increasing water depth was observed in other lakes as well (Bloesch 1994; Evans 1994; Leemann and Niessen 1994). In Lake Stechlin (Mothes 1985) the total mass flux of the sediment increased by a factor of 1.7 between 20 and 40 m of the water depth.

Table 1 Comparison of the share of the basic sediment components, i.e. CaCO₃, OM and SiO₂, in the bulk sediments accumulated in the sediment traps during the late autumn water mixing, winter stagnation and spring and summer productivity

Season	CaCO ₃				OM			
	16 m		30 m		16 m		30 m	
	Mean flux (g m ⁻² day ⁻¹)	% Of the bulk sediment	Mean flux (g m ⁻² day ⁻¹)	% Of the bulk sediment	Mean flux (g m ⁻² day ⁻¹)	% Of the bulk sediment	Mean flux (g m ⁻² day ⁻¹)	% Of the bulk sediment
Late autumn (13.11–18.12)	2.1	58.3	4.0	61.5	0.7	19.4	1.3	20.0
Winter (18.12–17.03)	0.5	45.5	0.8	53.3	0.2	18.2	0.3	20.0
Spring and summer (17.03–13.09)	3.3	62.4	3.1	57.9	1.0	18.4	1.0	18.2
Season	SiO ₂				Bulk sediment			
	16 m		30 m		16 m		30 m	
	Mean flux (g m ⁻² day ⁻¹)	% Of the bulk sediment	Mean flux (g m ⁻² day ⁻¹)	% Of the bulk sediment	Mean flux (g m ⁻² day ⁻¹)	% Of the total flux	Mean flux (g m ⁻² day ⁻¹)	% Of the total flux
Late autumn (13.11–18.12)	0.8	22.2	1.2	18.5	3.6	10.9	6.5	17.3
Winter (18.12–17.03)	0.4	36.4	0.4	26.7	1.1	8.4	1.5	10.2
Spring and summer (17.03–13.09)	1.0	19.2	1.3	23.9	5.2	80.7	5.3	72.5

Winter

The mean sediment flux to the traps was the lowest between 18th December 2015 and 17th March 2016 (Fig. 6a) when primary productivity contribution to the sediment accumulated was significantly limited. Low sediment flux points to the limited role of resuspension and redeposition during the winter stratification, however, those processes cannot be totally excluded. Slow sedimentation of the smallest particles from the suspension is regarded to contribute to the winter sediment flux in Lake Kierskie. The greater total sediment flux in the deeper sediment trap (Table 1) indicates sediment focusing with increasing depth. The proportions between CaCO_3 , OM and the remaining material (likely SiO_2) in the sediments collected during the winter differ from the late autumn, spring and summer seasons (Table 1). This change relates mainly to the decreased share of CaCO_3 and an increased amount of the remaining material. A smaller percentage of CaCO_3 in the sediments is a consequence of lack of calcite precipitation in the epilimnion and the dissolution of the carbonates indicated by the negative calcite SI values (Fig. 6h; ESM 1).

Spring and summer

In contrast to the substantial contribution of redeposited material to the sediment traps in the autumn, we did not observe increased sediment accumulation in the traps during the water turnover in the early spring (Figs. 4, 6a). The difference observed may relate to the length of the mixing period. The prolonged period of relatively equal air temperatures during most of October, November and December 2015 (Fig. 6e) was suitable for establishing of the equalized temperatures of lake waters and long water mixing (Fig. 4). On the contrary, in the early spring temperatures increased fast and the length of water mixing was limited (Figs. 4, 6e). It seems possible that thickness of the laminae deposited during the water turnover is a potential indicator of the duration of the water mixing, with thicker laminae formed in the years with longer homothermy in the water column and long period of water mixing. However, this suggestion should be verified by further studies.

Phytoplankton bloom started already during the spring water mixing when nutrients became available

in the epilimnion. The phytoplankton assemblage was dominated by centric diatoms *Stephanodiscus hantzschii* and *Cyclotella* sp. (Figs 4, 5; ESM 2). Some of the diatom species could have bloomed under the ice (Vehmaa and Salonen 2009) that discontinuously occurred on the lake. The coincidence of the maximum biomass and abundance of the diatom species (Fig. 5) with the water mixing during the lake turnover (Fig. 4) in the early spring is typical for this group of phytoplankton (Reynolds 2006). Regarding their build, i.e. lack of flagella and therefore the disability to move, and heavy siliceous shell, diatoms are a group of phytoplankton characterized by the fastest sedimentation rates among the phytoplankton (Sommer 1984; Padišák et al. 2003). As was evidenced by Smetacek (1985), diatoms of the size of *S. hantzschii* settle down very rapidly and within one day they can reach the sediment traps installed at the depth of 30 m. What keeps diatoms in suspension is the presence of water movement (waves, mixing; Fuchs et al. 2016). Under windless conditions and establishing of the stratification, the sedimentation rate of diatoms increases instantly (Padišák et al. 2003). Accordingly, in Lake Kierskie mixing of the water column in March (Fig. 4), allowed to prolong the time of diatom suspension (Fig. 5; ESM 2) and contributed to the bloom of this group of phytoplankton. Interestingly, the maximum biomass and abundance of the diatom species preceding the onset of stratification in Lake Kierskie (Figs. 4, 5; ESM 2) is in contrast to observations by Kienel et al. (2017) from Tiefer See, who evidenced the peak of phytoplankton concentrations, dominated by diatom assemblages, right after the onset of stratification, and concentration of the diatoms within the photic layer of the lake water. The discrepancy observed may result from the different methodology used. The diatom data of Kienel et al. (2017) are based on sediment samples collected from traps in 15-day intervals, therefore with a time lag, whereas we have described an actual phytoplankton assemblage and corresponding limnological conditions.

In Lake Kierskie the maxima of the phytoplankton biomass are clearly reflected in the physical and chemical properties of water, namely in the second-highest content of chlorophyll-*a*, during the monitoring period, the peak of O_2 concentration in water, and marked decrease in Secchi disk visibility (Fig. 6i, j). Domination of the phytoplankton assemblage by

centric diatoms (Fig. 5; ESM 2), resulted in a very strong increase in SiO_2 content in the sediments, considerably higher to the sediment traps installed at 30 m (Fig. 6d), indicating sediment focusing. Observations from Lake Kierskie agree with the increased sedimentation rate observed after spring diatom bloom in lakes Constance (Grossart and Simon 1998) and Holzmaar (Moschen et al. 2006).

The spring phytoplankton bloom is also recorded in increased OM content in the sediments (Fig. 6c). Intensive primary productivity in the pelagial zones of lakes with waters rich in dissolved calcium and bicarbonates results in precipitation of CaCO_3 (Rodrigo et al. 1993). The biological precipitation of calcium carbonate occurs when the CO_2 assimilation during photosynthesis increases pH and causes supersaturation of water with bicarbonates (Yates and Robbins 1998). In the pelagic zone the cells of planktonic algae and cyanobacteria (Cyanoprokaryota), particularly their finest fraction, autotrophic picoplankton (APP), were shown to serve as crystallisation nuclei, indispensable in the precipitation of CaCO_3 (Dittrich and Obst 2004). In Lake Kierskie, despite the intensive primary productivity and active biological assimilation of CO_2 , visible in the increased pH value, the amount of CaCO_3 collected in the traps between March and April increased only slightly (Fig. 6b, f). The agent blocking precipitation of calcium carbonates were PO_4^{3-} ions (Kelts and Hsü 1978) abundantly present in the epilimnion (Fig. 6k). Enhanced CaCO_3 precipitation started only after the phosphorus ions were assimilated by the primary producers and their concentration in epilimnion decreased. These observations agree with data provided from other lakes (Teranes et al. 1999; Bluszcz et al. 2009). In Lake Kierskie the maxima of carbonates accumulation were observed between mid-April and mid-June (Fig. 6b) and were synchronous with the domination of *S. hantzschii*, diatom evidenced to have the inductive role in the CaCO_3 precipitation in Lake Constance (Stabel 1986). However, Stabel (1986) did not exclude the potential role of many other phytoplankton species in this phenomenon, especially small flagellate forms acting as nucleation sites. Such a species is *P. nannoplantica* characterized by the greatest share in the total number of phytoplankton individuals in this time period, particularly in April when the species was not only numerous but also

significantly contributed to the biomass production by phytoplankton (Fig. 5; ESM 2).

Oversaturation of waters with CaCO_3 was also due to a rapid increase in temperature of the epilimnion (Fig. 6e, h) and degassing of aquatic CO_2 . However, the maxima of CaCO_3 accumulation between 15th April and 25th May (Fig. 6b) result probably not only from enhanced calcite precipitation but also conditions favourable for calcite preservation in the sediments. As observed on 15th April SI values were positive at 16 and 30 m, in contrast to those observed later during the productive season (Fig. 6h). Such conditions prevented carbonates dissolution. Sediment focusing between 15th April and 25th May is evidenced by the higher CaCO_3 flux to the sediment traps installed at 30 m compared to the traps at 16 m (Fig. 6b).

In subsequent months, despite the positive calcite SI values in the epilimnion, the amount of CaCO_3 flux to the sediment was constantly decreasing (Fig. 6b, h). A drop in CaCO_3 precipitation was observed already in May and June and was simultaneous with a decrease in the biomass of *S. hantzschii*. Phytoplankton dominance shifted towards the species which in the Stabel (1986) opinion do not interfere with the Ca equilibrium in the water. Among them, a large species, *Ceratium hirundinella*, became dominant. This also concerns the cryptophyte *P. nannoplantica*, whose share in the total biomass increased along with the *S. hantzschii* decrease (Fig. 5; ESM 2). However, based on the gradually decreasing Ca^{2+} concentration in the epilimnion, negative and constantly decreasing calcite SI values and an increasing Ca^{2+} concentration in the hypolimnion, especially at 30 m (Fig. 6g, h), it is suggested that the actual CaCO_3 flux was greater than measured in the sediment traps as the carbonates were partially dissolved. This suggestion is supported by lower CaCO_3 flux to the sediment traps installed at 30 m, i.e. the longer calcite crystals settling time in the water column along with lower water temperatures could have resulted in more CaCO_3 being dissolved (Ramisch et al. 1999). Despite the decreased amount of CaCO_3 collected, its contribution to the sediment was still the greatest among the basic geochemical components of the sediments (Fig. 6b). Change in the proportion between SiO_2 and OM from early spring to the succeeding productive months reflects a shift from the diatom-dominated phytoplankton assemblage to

the communities composed of chlorophytes, cryptophytes, and dinoflagellates, the groups with cellulose external covering (Figs. 4c, d, 5).

During the summer stratification rapidly progressing extent of the hypoxic conditions was observed in the hypolimnion (Fig. 4). In September anoxic waters, with O_2 concentration below 1 mg l^{-1} , extended between 4 meters below the lake surface and the lake bottom. Such a strong oxygen depletion in the hypolimnion of lake Kierskie is driven by oxic degradation of organic matter supplied from the epilimnion of this highly productive lake. Oxic conditions in the hypolimnion were not improved by aerators installed in the lake that release the oxygenated waters at about 14 m of the water depth and theoretically should increase the oxygen content in the waters. On the other hand, O_2 released by aerators may have been instantly used in the process of organic matter decomposition. Although the operation of the aerators in Lake Kierskie is beyond the scope of the present study, the prevailing hypoxic or even anoxic conditions observed in the water column may question their effectiveness. One year of monitoring study does not entitle us to a broader discussion of this issue, however preservation of the laminated sediments in the upper 0.5 m of the sediment sequence (Fig. 2b), though indirect, seems to be a solid record of sustained hypoxia in Lake Kierskie during the winter and summer stratification, despite the 31-years of efforts to oxygenate the waters. The very limited influence of aerators in Lake Kierskie is not an exception. It was shown (Jenny et al. 2016a) that implementation of restoration programs failed to turn off of hypoxia in many European and North American Lakes. Release of the oxygenated waters in the lake hypolimnion can influence geochemical processes in the hypolimnion, including oxic degradation of the organic matter, and therefore modify the sedimentary record. The exact influence of the aerators on the lake and the sediments may be determined only by a detailed analysis of sediment laminations, distinguishing the laminae deposited before and after installation of the aerators. Assuming seasonality of the laminae formation in Lake Kierskie, it is possible to determine the exact lamina deposited in the year when aerators were installed in the lake.

Late summer–early autumn

The early autumn phytoplankton bloom, recorded in the maximum chlorophyll-*a* values and water transparency restricted to merely 0.9 m (Fig. 6i, j), was observed in mid-September. Water turnover did not start yet, which is indicated by stratification of all the physico-chemical parameters (Fig. 4, ESM 1), therefore nutrients may not have been returned to the epilimnion from hypolimnion. According to data on nutrient loadings in the inflows supplying Lake Kierskie (Grzonka et al. 2016), an increase in TP concentration (0.058 mg l^{-1} in July, 0.105 mg l^{-1} in August and 0.152 mg l^{-1} in September) was observed in the River Krzyżanka, supplying the southern part of Lake Kierskie, where our monitoring study was carried out. This additional nutrient supply could have stimulated the growth of the early autumn phytoplankton assemblage. External sources of nutrients related to human activity, e.g. catchment inputs delivered by inflows, can be highly variable in time and significantly influence the natural processes. The phytoplankton bloom was evidenced in the epilimnion but not in the deeper water layers (Fig. 5; ESM 2) and was caused by the dinoflagellate *C. hirundinella* that due to large cell sizes and ability to move by means of flagella stays longer in the epilimnetic waters and avoids fast sinking. The biomass produced by phytoplankton in late summer and early autumn indicates highly eutrophic waters, or even hypertrophic if the September biomass value and chlorophyll-*a* concentrations are considered (Table 1; Fig. 6i). The hypertrophic conditions were not followed by the cyanobacterial dominance, which is rather expected in conditions of high water fertility (Fig. 5; ESM 2). Despite the still high calcite SI values in the epilimnion (Fig. 6h), the early autumn phytoplankton bloom did not result in massive calcite precipitation (Fig. 6b), which was probably prevented by the dominance of *C. hirundinella*, species regarded as negligible in the CaCO_3 precipitation (Stabel 1986). Loss of the sediment traps (stolen between 13th September and 18th October 2016) prevents the determination of the quality and quantity of the sediment accumulated as a result of the late-summer–early-autumn bloom in productivity.

Yearly record of laminated sediments in Lake Kierskie based on the sediment trap study

The most recent laminations in Lake Kierskie are distinct and thick (Fig. 2b). Based on the macroscopic investigation of the short core, the pale, whitish lamina is followed by dark, greyish or black lamina (Fig. 2b). Such a sequence of laminae is confirmed by the sediment flux to the lake bottom recorded by us in a 1-year, monthly sediment trap study (Fig. 6b–d).

Whitish lamina is expected to record chiefly the strong CaCO_3 flux from the epilimnion during spring and summer seasons (Fig. 6b). The lamina should start with a layer of centric diatoms that bloomed during the early spring water mixing that resulted in a strong pulse of SiO_2 to the sediments (Fig. 6d). The sedimentary record of the early spring phytoplankton bloom is expected to overlap and to be followed by the layer dominated by small calcite crystals, as evidenced by the smear slide analysis of the trap sediments, a record of rapid precipitation from waters oversaturated with respect to calcite. Considering the results of the smear slide analysis, towards the upper limit of the whitish lamina bigger calcite crystals should occur indicating CaCO_3 precipitation during late spring and summer when the oversaturation decreased. However, as was shown by Ramisch et al. (1999) in two deep meromictic lakes (288 and 87 m deep), the eventual record of calcite crystals preserved in the sediment may contain a proportionally greater share of larger crystals compared to the size distribution of calcite crystals initially precipitated in the epilimnion. Ramisch et al. (1999) showed that smaller crystals, $< 20 \mu\text{m}$, are easily dissolved and rarely reach the bottom of deep lakes. Although Lake Kierskie is much shallower (35 m in the deepest place), calcite dissolution was proven by increased Ca^{2+} concentration in the hypolimnion during summer stratification (Fig. 6g) and therefore syn- and postdepositional change in the proportion between small and large calcite crystals must be considered in the detailed examination of the laminae. In lake Kierskie all calcite crystals observed had a typical for calcite crystallographic form of rhombohedra.

The dark (greyish or black) lamina (Fig. 2b) is considered to record sediment deposition during autumn and winter. Following the results of the sediment trap study, it may be subdivided into thicker lamina deposited during or shortly after water

turnover, and lamina formed during winter stratification (Fig. 6a). However, this subdivision is based solely on the data from the sediment trap study and must be verified by a microscopic examination of the sediments. The thickness of the lamina deposited during autumn may be an indicator of the water overturn duration in Lake Kierskie, with the thicker lamina being a potential record of prolonged water mixing during homothermy. The sediment accumulated during and after resuspension should be composed of mixed sediment components typical of sedimentation during different seasons, e.g. centric and pennate diatoms and calcite crystals of different sizes. Theoretically, the winter lamina should be the thinnest one and composed primarily of the smallest particles deposited from the suspension. Low sediment flux during winter (Fig. 6a) resulted from the break in the primary productivity in the epilimnion. Stratification of lake waters and discontinuously occurring ice cover protected the deep waters from mixing and sediment resuspension. As showed by the sediment trap study, winter lamina is expected to contain a smaller percentage of calcite crystals in the sediments, a consequence of lack of CaCO_3 precipitation in the epilimnion and the dissolution of the carbonates indicated by the negative calcite SI values (Fig. 6h; ESM 1).

Yet another sediment lamina composed of the resuspended material can potentially form during the spring water mixing. However, the material redeposited during the spring lake turnover can be mixed with the flux of the sediment particles from epilimnion, resulting from the bloom of centric diatoms peaking at the water mixis. In spring 2016 an increase in the air temperature and therefore also of Lake Kierskie surface waters was fast (Fig. 6e). Thermal stratification prevented significant resuspension and redeposition of the sediments in the lake.

The results of the one-year monthly monitoring study in Lake Kierskie does not allow us to detect the interannual changes in limnological conditions and sediment flux to the lake bottom as was shown by Bonk et al. (2015), Rull et al. (2017) and Trapote Mari et al. (2018). The planned by us, multi-year monthly monitoring study was interrupted by removal/theft of the traps between 13th September and 18th October 2016. Sediment trap loss was frequently encountered during the CLIMPOL Project (Tylmann, personal communication), therefore our case is not an

exception. Considering the location of Lake Kierskie in a densely populated area, its recreational character in the summer, and a year-round presence of fishers on the lake, we did not decide to install the new traps because of a high probability of their repeated loss.

Potential of laminated sediments from Lake Kierskie as a seasonal palaeoenvironmental archive

Lake Kierskie is characterized by a combination of several prerequisites necessary for the formation and preservation of annually laminated sediments (Zolitschka et al. 2015; Tylmann et al. 2013). The study lake is funnel-like shaped with currently significant depth of 35 m (Fig. 1). Considering the 14-m-thick sediment sequence recovered from the deepest part of the lake, the maximum depth of the lake could have been at least 48 m shortly after the lake was formed. Due to prevailing steep slopes in the lakes direct surroundings, the surface area of the lake was not much greater in the past, even if the water level was higher. In consequence, the presently low exposure index (28.3) must have been even lower. In such conditions, the deep waters were even better protected from wind-induced mixing. Moreover, the longitudinal extension of the southern basin of Lake Kierskie is perpendicular to the dominating winds from W and WN direction (Woś 1994). Therefore, during the dominating winds the fetch, and therefore also the wave, is short and the depth of water mixing is restricted.

Despite the potentially favourable morphometric characteristics of the lake and its surroundings, the discontinuous character of laminated sediments was observed in the long core drilled in Lake Kierskie (unpublished data). Such a sediment record indicates that either yearly variability in the seasonal flux to the lake bottom was smaller when the massive, homogeneous sediments were deposited, or conditions at the lake bottom did not support the preservation of the laminated sediments. Because the lake is located in the temperate climate with distinct differences between the seasons, influencing primary productivity in the lake, and therefore also sediment flux to the lake bottom, the first hypothesis seems unlikely. Fragments of the sediment sequence where massive deposits are present refer to the times when the record of seasonal signal in the sediments must have been damaged by

postsedimentary processes, most likely related to the activity of benthic organisms, presence of which indicates oxic conditions at the lake bottom. The most suitable conditions for varve formation are found in meromictic lakes where the permanent density gradient between the surface and deeper waters develop and the deepest basin of the lake is isolated from mixing and oxygenation (Tylmann et al. 2013), and thus prevents the abundant presence of benthic fauna. Sediments deposited in such conditions have a great potential to record undisturbed seasonal environmental changes. Despite the documented dimictic character of Lake Kierskie and distribution of the oxygenated waters to the lake bottom during the water overturn in the spring and autumn, laminated sediments are well preserved in the top 50 cm of the sediment sequence (Fig. 2b). What prevents the abundant occurrence of the benthic fauna and, thus, protects the most recent laminated sediments from destruction by bioturbations are hypoxic toward anoxic bottom waters during stratification of the lake in the winter and summer (Fig. 4). Similarly, in Lake Montcortès Trapote Mari et al. (2018) observed continuous record of varved sediments despite the interannual shifts between meromictic and mictic states, and temporarily oxic conditions at the lake bottom. In Lake Kierskie the recent strong hypoxia of the hypolimnion is related to the high amount of organic matter supplied from the epilimnion as a result of high nutrient loading to Lake Kierskie controlling the enhanced productivity in the lake. Majority of the lakes with laminated sediments distinguished in NE Poland by Tylmann et al. (2013) were eutrophic, only some mesotrophic. Water hypoxia in response to nutrient loading was shown to be a key factor in the formation and preservation of laminated sediments in lakes across Europe (Jenny et al. 2016a). Concluding, shifts between laminated and massive sediments observed in the long core from Lake Kierskie can indicate changes in the oxygen availability at the lake bottom controlled by the lake trophic conditions. Nevertheless, the formation of the laminated sediments could have been also controlled by other factors affecting the stability of the lake stratification like climatic changes or water level fluctuations (Pleskot et al. 2018; Woolway and Merchant 2019). Therefore, the theoretically undesired in palaeolimnological studies discontinuous character of laminated sediments in Lake Kierskie can be a valuable record of climatic or lake-specific

changes, shifting the lake between the laminae preserving and non-preserving states.

Considering the dimictic character of Lake Kierskie the record of seasonal laminae can be destroyed by sediment resuspension induced by the water overturn. However, it has been shown by us that, at least at present, resuspension of the sediment during the water overturn, results in an additional flux of the material, but is not destructive to laminations in the deepest part of Lake Kierskie where the long and short cores were taken.

Potentially, the sediment record of laminated sediments in Lake Kierskie can also be affected by gravity-induced slumping of sediment and turbidity currents. Development of underwater mass movements is favoured by the steep slopes (up to $\sim 14^\circ$) of the Lake Kierskie southern basin and absence of the flattened surface at the lake bottom. Water saturated sediments are prone to gravitational movements induced by the sediment loading or triggered by waves disturbing the sediments in the shallower parts of the lake (Zolitschka et al. 2015).

Conclusions

A year-round monthly sediment trap study conducted along with water and phytoplankton monitoring allowed to recognize the conditions of the recent formation of biogenic laminated sediments in Lake Kierskie, western Poland. A yearly monitoring of the sediment flux to the traps displayed a clear seasonal pattern interrelated with physical and chemical characteristics of Lake Kierskie waters, the annual cycle of water mixing and stratification, and the primary productivity, which directly or indirectly controlled the formation of the three major sediment constituents, i.e. OM, CaCO_3 and $\text{SiO}_{2\text{biog}}$. The highest sediment flux to the traps was observed during the peak of primary productivity in spring and was promoted by the high water fertility in the studied lake. It began with the strongest flux of the diatom originating SiO_2 between mid-March and mid-April, which preceded the very intensive calcite precipitation later in the spring. The peak in CaCO_3 flux corroborated with the domination of centric diatom, *Stephanodiscus hantzschii*, species considered to have the inductive role in the CaCO_3 precipitation, and abundantly occurring small flagellate forms acting as nucleation

sites for carbonates. CaCO_3 precipitation continued in the summer, however at decreased intensity, simultaneously the biomass of *S. hantzschii* became lower. The second maximum of the sediment flux was observed during the late autumn and was related to resuspension and redeposition of the previously deposited sediments triggered by mixing of the water column. As documented by the preservation of the laminated sediments in the deepest parts of Lake Kierskie, the resuspended sediment must origin from the shallower parts of the lake bottom. Interestingly, increased sediment accumulation in the traps during the water turnover in the early spring was not observed. The difference observed may relate to the length of the mixing period. The prolonged period of stabilized temperatures during autumn promoted an extended period of water turnover and sediment resuspension. On the contrary, in the early spring temperatures increased fast and the length of water mixing was limited. The smallest flux to the traps was observed during the winter stratification when neither primary productivity nor sediment resuspension and resedimentation contributed to the sediment record. Slow sedimentation of the smallest particles from the suspension is regarded to contribute to the winter sediment flux in Lake Kierskie.

The sediment flux to the lake bottom recorded by us in a 1-year, monthly sediment trap study matches a sequence of pale, whitish lamina deposited during spring and summer, followed by dark, grayish or black lamina deposited in the autumn and winter, observed in the macroscopic investigation of the short (0.5 m) core from Lake Kierskie. Preservation of the seasonal character of laminations in Lake Kierskie despite the dimictic character of this lake is possible due to the prevailing hypoxic or anoxic conditions at the lake bottom during water stratification. Oxygen shortage is triggered by the high biogenic productivity in the highly eutrophic, or even hypertrophic waters of Lake Kierskie.

Results of the actualistic approach used in the present study are essential for accurate palaeoenvironmental reconstructions based on the record of laminated sediments from Lake Kierskie and are expected to be of value in the studies of other biogenic varved sediments that aim to reconstruct eutrophication impact on lake ecosystem in a temporal scale beyond instrumental record.

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