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Tracking climate signals in varved lake sediments: research strategy and key sites for comprehensive process studies in the Masurian Lakeland

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Abstract: Lake sediments are excellent archives of environmental and climate change. Especially important are varved sediments which can provide high-resolution (annual) records of those changes. Process studies including limnological measurements, particle flux monitoring and analyses of sediment structures give an opportunity to explain relationships between meteorological conditions, in-lake processes and varve formation. In our study, three lakes were selected in the Masurian Lakeland: Lake Żabińskie, Łazduny and Rzęśniki. These relatively small and deep lakes contain well preserved biogenic varves. The lakes are influenced by the same meteorological conditions but differ in terms of their catchment size, land use, hydrology, lake basin morphology and trophic status. To explore the relationships between different parameters and preservation/transformation of climate signals in the sediments we started systematic limnological measurements in the water column of these lakes, water sampling for hydrochemical analyses, monitoring of modern sedimentation using sediment traps and analysis of topmost varves from short sediment cores. With this comprehensive and high-resolution monitoring program scheduled for at least four years we are going to verify the potential of varves to track short-term meteorological phenomena in lake sediments.

Key words: lake sediments, varves, process studies, sediment trap, monitoring

Introduction

Natural archives containing yearly information such as varved lake sediments have invaluable scientific potential for reconstructions of past climate changes, accurate interpretation of the present-day situation and for reliable projections of future change (PAGES 2k consortium 2013). Lake sediments record physical, chemical and biological conditions and processes in the lake water body as well as the surrounding catchment on different temporal scales (Zolitschka et al. 2015). Moreover, varves have the best potential to investigate the preservation of climate signals because deposition of abiotic and biotic components can be calibrated with instrumental data. Even short-term changes in sediment composition can be observed and analyzed from varves using high-resolution analytical methods (Tiljander et al. 2002; Francus et al. 2009; Butz et al. 2017). The opportunity to investigate sediment response to meteorological conditions on subannual timescales seems unique and promising.

While lake sediments are widely used and studied in the scientific literature, actually very little is known about the specific processes (documented with observational data) that lead to sediment formation and signal preservation in a particular lake setting. The documentation of climate signals preserved in varves requires comprehensive process studies that combine limnological monitoring, sediment trapping and sediment analysis (Bigler et al. 2012; Ojala et al. 2013). It has been shown that process studies are the best way to identify processes responsible for sediment formation and provide a key to understand the paleorecord (e.g. Leemann and Niessen 1994; Lamoureux 1999; Bluszcz et al. 2008; Stockhecke et al. 2012; Tylmann et al. 2012; Bonk et al. 2015a). These studies have shown that in clastic environments the deposition of varves is mainly a function of hydrometeorological parameters but for biogenic sediments the mechanism of varve formation is usually very complex and influenced by interactions of physical, chemical and biological processes. Therefore, assessing past environmental conditions from

biogenic varves is not straightforward. Relations between climate indices and different parameters of biogenic varves have rarely been identified (e.g. Zolitschka 1996, Lotter and Birks 1997; Kienel et al. 2013, 2017), but it was established that for biogenic varves only part of the variance in varve thickness is explained by climatic influences (Lotter and Birks 1997). However, only little is known about other varve characteristics (varve structure) and their relations to meteorological parameters. This knowledge is vital for a more meaningful and process-oriented interpretation of environmental information that may be extracted from varved lake sediments.

Northeastern Poland has many potentially promising lacustrine sediment archives that contain biogenic varves (Tylmann et al. 2013). They offer the potential for high-resolution, quantitative reconstruction of environmental changes, applying a range of biological, sedimentological and geochemical proxies (e.g. Hernández-Almeida et al. 2015; Larocque-Tobler et al. 2015; Bonk et al. 2016; Wacnik et al. 2016; Hernández-Almeida et al. 2017). Potential connections between seasonal meteorological conditions, modern sedimentation dynamics and different varve structures have been signalized by Bonk et al. (2015a), yet these relationships are still not fully recognized. So far, a key limitation to most field process studies has been their short-term nature of often only 1–2 years. In many cases it is not enough to decipher complex mechanisms that influence preservation of climate signals in sediments.

In this paper we present our research strategy and key sites for a newly established project aiming at long-term (4 years) and high-resolution monitoring of three lakes in the Masurian Lakeland in order to explain relationships between meteorological conditions and biogenic varve formation in the investigated lakes, and also to demonstrate the possibilities and limitations of tracking short-term weather-scale atmospheric phenomena in lake sediments. The overall research questions are: (*i*) Does regional climate and lake stratification/mixing patterns play a major role for sedimentation processes?; (*ii*) How are climate and other environmental signals preserved in sediments? To what extent are they interpretable? and (*iii*) Is it possible to investigate short-term meteorological events using lake sediments? To answer these questions, we will (*i*) identify meteorological, limnological and hydrochemical conditions that control sedimentation processes in the investigated lakes; (*ii*) document how seasonal and short-term variations of meteorological conditions are reflected in the structure of varves deposited during the observation period and (*iii*) validate varve microstructures for reconstruction of meteorological parameters for the last approximately 100 years by linking them with available instrumental data. The scientific plan and preliminary characteristics of three varved lakes and their catchments are presented herein. The lakes provide ideal conditions for tracking how climate signals are preserved in the sediments, modified or overprinted by different processes.

Study area

The Masurian Lakeland is located in northeastern Poland and extends eastwards from the low Vistula river to the borders of Lithuania and Belarus. It forms a west belt of postglacial landscapes with the highest areal density of lakes in Poland, in some parts reaching up to 20% (Choiński 2007). Lakes here are diversified in terms of hydrological regimes, morphometry, trophic states and water chemistries. Many of them contain varved sediments which makes the Masurian Lakeland an ideal area for investigations of past environmental change (Tylmann et al. 2013).

The surface geology of the Masurian Lakeland is dominated by the sediments deposited during the Pomerian phase of the Vistulian glaciation (16–15 ka BP). The most common are glacial and glacifluvial deposits including moraine tills, sands and gravels, which

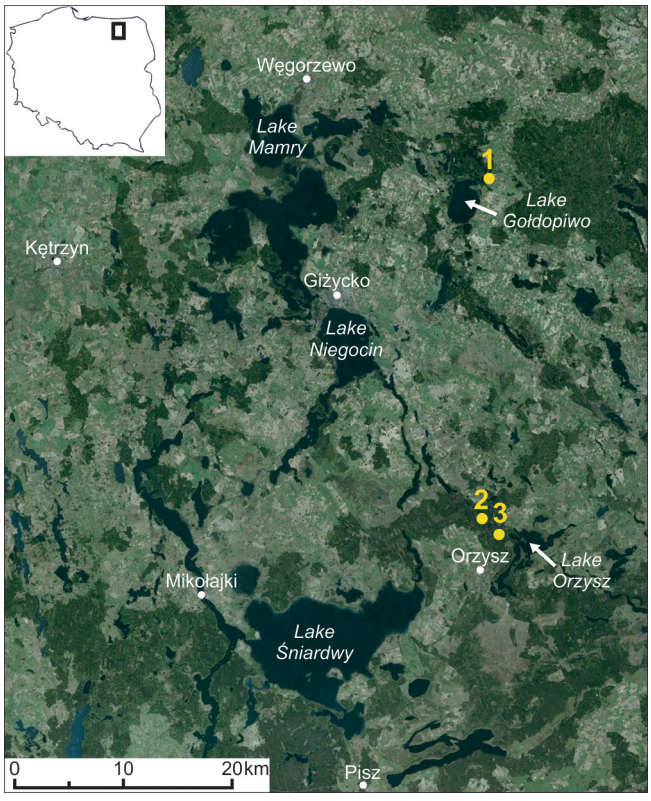

Fig. 1. Location of the study sites in the Land of Great Masurian Lakes
1 – Lake Żabińskie, 2 – Lake Łazduny, 3 – Lake Rzęśniki

build the moraine plateaus and moraine hills. Holocene sediments are represented mainly by fluvial and organic deposits. The thickness of these Quaternary deposits ranges from dozens to over 200 m. The topography of this area is diverse with elevations generally in the range 50–300 m a.s.l.

The climate in the Masurian Lakeland is characterized by strong continentality and seasonality (warm summers and cold winters). The mean annual air temperature is about 7–8°C with the lowest mean monthly temperatures occurring in January (form –3 to –2,5°C) and the highest temperatures in July (17–18°C). Annual precipitation ranges from 550 to 600 mm reaching its highest values in June (ca. 80 mm) and lowest in February (ca. 25 mm) (Lorenc 2005). Lakes in the region are covered with ice generally between December and April (Marszelewski and Skowron 2006).

Two dominant soil types in the region are podzols and cambisols (Bednarek and Prusinkiewicz 1999). Woodland communities cover about 30% of the region with domination of coniferous forests (80%). The major part of the area is occupied by arable lands (ca. 50%). Other types of land use cover ca. 20%.

Methods

The research plan benefits from previous studies describing the distribution of lakes with laminated sediments in northeastern Poland (Tylmann et al. 2013) as well as from the Polish Training Set which was established in northern Poland based on the statistical selection procedure presented in detail by Hernández-Almeida et al. (2015). 50 lakes located across northern Poland were selected and monitored using sediment traps with annual resolution during the years 2011–2015. Based on this material we selected 3 lakes with the highest potential for process studies: Lake Żabińskie (54°07'54.2"N, 21°58'56.5"E), Lake Łazduny (53°51'18.3"N, 21°57'07.1"E) and Lake Rzęśniki (53°50'30.0"N, 21°58'35.9"E) (Fig. 1). The lakes are located in the Land of Great Masurian Lakes, therefore overall climatic conditions are the same. They are small, relatively deep and in all of them biogenic varves are excellently preserved. However, they are different in terms of trophic status, hydrological regime, catchment size and land use. Such a selection gives an opportunity to track how the climate signal is transformed/preserved in the sediments of these lakes.

The general strategy of the planned process study consists of three pillars: (1) on-site measurements of the water column environment, (2) particle flux measurements and (3) analysis of the uppermost sediments from short cores, to understand the relation between overall meteorological conditions, weather-scale atmospheric phenomena, lake water properties and sediment formation in the investigated lakes.

Physical, chemical and biological parameters (temperature, conductivity, pH, oxygen concentration, turbidity, chlorophyll-*a* concentration, blue-green algae concentration) of the water column are measured on-site with bi-weekly resolution using a multiparameter sonde. Water samples are collected from epi-, meta- and hypolimnion for analyses of (1) nutrient concentrations (TN and TP) measured using colorimetric methods, (2) concentrations of major cations (Na^+, Ca^{2+}, Mg^{2+}, K^+) and anions (SO_4^{2-}, Cl^-) determined by ion chromatography and (3) HCO_3^- measured by standard titration methods. Details of laboratory procedures are provided in Bonk et al. (2015a).

In each lake, an automated sequencing sediment trap is deployed for the monitoring of particle fluxes at a temporal resolution of two weeks. The collected samples are used for the preparation of smear slides and freeze dried to estimate sediment fluxes. Total carbon (TC), total organic carbon (TOC), total inorganic carbon (TIC), total nitrogen (TN) and total sulphur (TS) contents in the sediment samples are determined using a CNS analyzer. Biogenic silica (BSi) concentrations are determined by the alkaline leaching method and ICP-OES corrected for lithogenic Si (Ohlendorf and Sturm 2008). Diatom and chrysophyte cyst analyses are conducted according to standard procedures (Battarbee 1986; Pla et al. 2003).

Short gravity cores with an undisturbed sediment-water interface will be split lengthwise and subsampled for thin sections following Lotter and Lemcke (1999). The impregnated slabs will be scanned using the micro-XRF technique (ITRAX Core Scanner) at the highest possible spatial resolution of measurements to obtain a sub-seasonal record of chemical element variability. VIS-RS scanning using a hyperspectral core scanner will provide an estimation of the variability in photopigments and clay mineral contents in the sediments (Butz et al. 2015). In the next step, thin sections will be prepared from impregnate slabs and investigated for varve composition using a petrographic microscope.

Initial results and interpretation

Catchment characteristics

The catchments of the investigated lakes are different in terms of their size, morphology and land use. The total catchment of Lake Żabińskie (24.6 km^2) extends eastward from the lake and consists of three subcatchments: Lake Żabińskie (3.8 km^2), Lake Purwin (7.5 km^2) and Lake Łękuk (13.3 km^2) (Fig. 2). In the eastern part of the catchment elevations exceed 200 m a.s.l. and decrease generally in a westerly direction to a

minimum of 117 m a.s.l. which is the water level of Lake Żabińskie. Typical for postglacial areas, the surface geology of the catchment is diverse. The most common landform is a moraine plateau composed of glacial till. Moraine hills built of sand, gravels and boulders as well as kame hills built of silt and sand occur mainly in the northern and southeastern part of the catchment. The plateau is cut by river valleys filled with fluvial sediments. The westernmost part of the catchment is occupied by fluvioglacial sands and gravels. Peat bogs occur in waterlogged areas.

The lake drains westward through a short channel into the much larger Lake Gołdopiwo. However, during periods of strong westerly winds, the water may flow eastward from Lake Gołdopiwo to Lake Żabińskie. The major inflow enters the lake from the northeastern side and provides water from Lake Purwin. A second major creek flows from the south and forms a small delta situated close to the deepest part of the lake. According to Bonk et al. (2015b) it transports significant amounts of sediment particles and organic remains, especially after spring snowmelt and heavy rains in the summer. In contrast, inflow that enters the lake in the southeastern part is episodic and occurs mostly after heavy rainfalls.

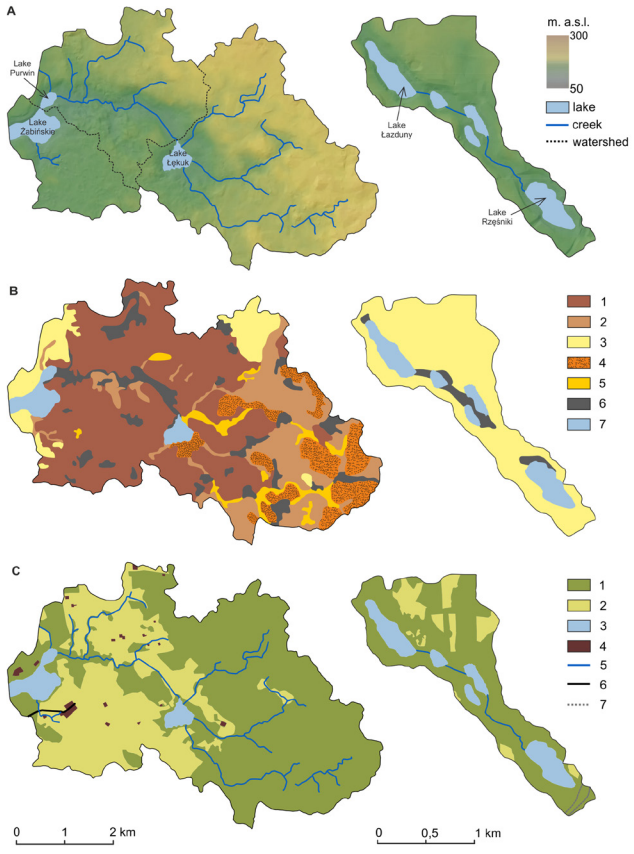

Fig. 2. Catchments of Lake Żabińskie (left) and lakes Łazduny and Rzęśniki (right)
A – Catchment topography. B – Surface geology (1 – moraine till; 2 – sand, gravel and till; 3 – sand and gravel; 4 – clay, silt and sand; 5 – humic sand and peat silts; 6 – peat). C – Land use (1 – forests; 2 – fields and meadows; 3 – lakes; 4 – build-up area; 5 – creeks; 6 – roads; 7 – railroad tracks). Based on Topographic Map of Poland 1:10000, Detailed Geological Map of Poland 1:50000 and orthophotomap (CODGiK, 2010).

Woodland communities cover ca. 65% of the total catchment surface, mainly in the eastern part of the catchment and are dominated by forests of pine, spruce and birch trees. Arable lands and meadows occupy the zone between Lake Żabińskie and Lake Łękuk. The village of Żabinka is located ca. 0.5 km southwest of the lake. Additionally, there is a recreation area on the north shore of the lake.

The catchment of lakes Łazduny and Rzęśniki (Fig. 2) is much smaller and homogeneous. The total catchment area (1.94 km^2) is elongated from NW to SE. In the northern part elevations exceed 153 m a.s.l. while the minimum of 125 m a.s.l. is the water level of Lake Rzęśniki. The entire catchment lies within an outwash plain built of glaciofluvial sand and gravel deposits. A chain of lakes is located in a deep subglacial channel that bisects the catchment along the NW–SE axis. The bottom of this channel is covered by peat deposits.

Lake Łazduny has no inflowing streams and one outflow towards the southeast. This creek flows through two small and shallow water bodies and enters Lake Rzęśniki in its northwestern part. The outlet from Lake Rzęśniki supplies water to the much larger Lake Orzysz located 700 m south-east of Lake Rzęśniki.

The entire catchment area is characterized by podsolic soils and luvisoils. Woodland communities cover ca. 85% of the total catchment with a dominance of coniferous trees. Only small uncovered places occur mostly in the northern part. There is no settlement in the catchment and human impact can be described as minimal.

Morphology of lakes

Lake Żabińskie occupies a glacially eroded depression formed during the Vistulian glaciation (Szumański 2000). It is a kettle hole basin most likely formed during the Late glacial with typical characteristics, i.e. small surface area (41.6 ha), approximately oval shape and considerable maximum depth (44.4 m) (Fig. 3). The lake basin is slightly elongated in a W–E direction and two parts can be distinguished: a shallow basin in the western part and a deep central basin surrounded by steep slopes in the middle of the lake. Mean depth (12.2 m) and a low value of exposure index (3.4) suggests good protection for the deep waters from wind-driven mixing (Table 1).

Lakes Łazduny and Rzęśniki occupy small elongated depressions (10.6 and 12 ha, respectively) and were formed probably by the melting of dead ice in a deep

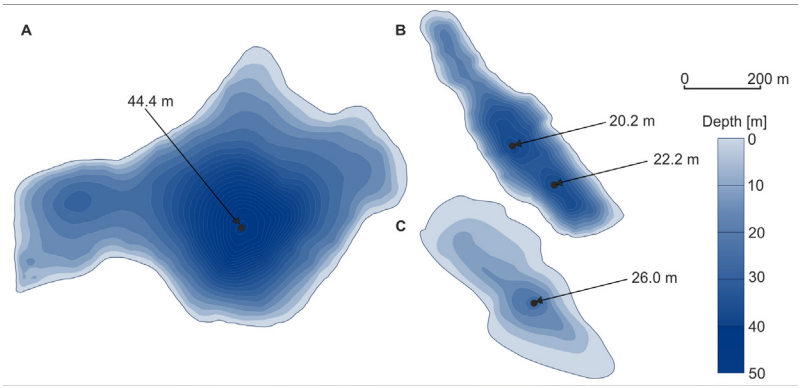

Fig. 3. Bathymetric maps of Lake Żabińskie (1), Lake Łazduny (2) and Lake Rzęśniki (3). Based on field bathymetric surveys and data from Jańczak (1999)

Table 1. Morphometric data for the lakes

Parameter	Lake		
	Żabińskie	Łazduny	Rzęśniki
Surface [ha]	41.6	10.6	12.0
Volume [tys m^3]	5072.8	964.6	1111.8
Maximum depth [m]	44.4	22.4	26.0
Average depth [m]	12.2	9.1	7.8
Maximum length [m]	1073	790	700
Maximum width [m]	635	210	280
Length of shoreline [m]	2846	1880	1700
Shoreline development index	1.2	1.6	1.3
Exposure index	3.4	1.2	1.8

channel of a glacial outwash plain. They both have relatively long (780 and 700 m), narrow (210 and 280 m) and deep (22.4 and 26 m) basins aligned along the main axis of the subglacial channel. The profundal parts of both lakes are very well isolated from wind-driven turbulent mixing as shown by extremely low values of exposure index (1.2 and 1.8). Lake Łazduny basin has a shallow NW part and two deep sub-basins divided by a submerged threshold. The slopes in central and SE parts are very steep. The morphology of Lake Rzęśniki basin is not diverse with the deepest place in the central part of the basin.

Limnology of lakes

To understand limnological processes and their relationships with sedimentation in the investigated lakes, systematic monitoring of physical, chemical and biological parameters in the water column has been started (Fig. 4, Table 2). Seasonal depth profiles of water temperature and dissolved oxygen show that these lakes have similar circulation patterns with strong summer and winter stratification of the water column which supports anoxic conditions in hypolimnetic waters. It is worth noting that during summer stratification oxycline was very sharp in all lakes and hypoxia already occurred in shallow waters. Anoxic conditions (<1 mg dm^{-3}) were recorded in Lake Żabińskie at a water depth of 8 m while in lakes Łazduny and Rzęśniki at 7 m. This means that, especially in Lake Żabińskie, most of the water column is anoxic. Results from 2017 also indicate that spring mixing might be incomplete in all lakes. In Lake Żabińskie, good oxygen conditions occurred from the surface to a water depth of 23 m while below the depth of 27 m anoxic conditions were still observed. Similarly, in lakes Łazduny and Rzęśniki dissolved oxygen concentrations >1 mg dm^{-3} were observed only to the depths of 15 and 14 m, respectively.

Table 2. A selection of hydrochemical parameters measured in epilimnion and hypolimnion

Depth [m]	pH	HCO_3^- [mg dm^{-3}]	Na^+ [mg dm^{-3}]	K^+ [mg dm^{-3}]	Mg^{2+} [mg dm^{-3}]	Ca^{2+} [mg dm^{-3}]	SO_4^{2-} [mg dm^{-3}]	Cl^- [mg dm^{-3}]	TN [mg dm^{-3}]	TP [mg dm^{-3}]
Lake Żabińskie										
1	8.74	158.64	4.11	1.22	10.01	57.11	22.75	10.26	1.28	0.07
40	7.36	216.61	3.96	2.15	10.66	72.60	21.43	10.12	1.74	0.17
Lake Łazduny										
1	8.29	158,64	4.65	1.05	11.13	54.78	19.98	17.81	0.70	0.04
20	7.29	176.95	4.69	1.15	11.43	59.90	20.21	17.83	1.08	0.10
Lake Rzęśniki										
1	8.29	195.25	2.96	0.49	9.95	59.73	18.62	7.20	0.46	0.04
25	7.34	210.51	2.92	0.76	9.10	64.71	18.28	7.06	1.57	0.22

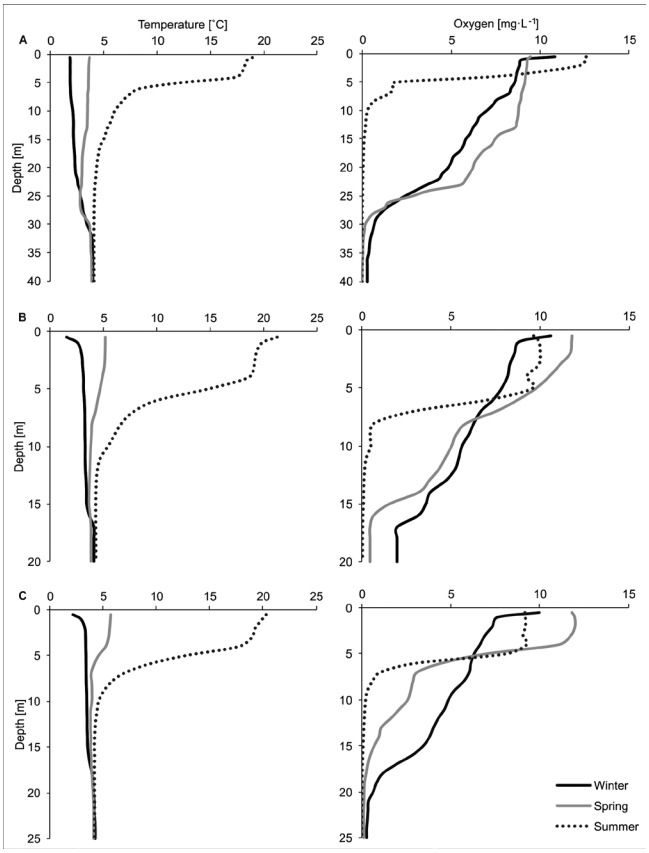

Fig. 4. Depth profiles of water temperature and oxygen concentration from different seasons
A – Lake Żabińskie, B – Lake Łazduny, C – Lake Rzęśniki. Measurements conducted on 18.02.2017, 27.03.2017 and 07.07.2017

The surface and near-bottom water chemistry of the lakes is presented in Table 2. The data shows that these are slightly alkaline hardwater lakes which is typical for postglacial landscapes of northern Poland and related to calcium-rich deposits in this area. The lake waters have a generally similar chemical composition with a distinct difference between surface and near-bottom waters. Enrichment with nutrients (TN and TP) in near-bottom waters is not surprising taking into account the weak mixing of the water column. Nutrients are accumulated in hypolimnetic waters during long periods of water column stratification. Additionally, internal loading from bottom sediments takes place under anoxic conditions (Özkundakci et al. 2011), which is also most likely the case in the investigated lakes.

Modern sedimentation

All three lakes accumulate varved sediments of the same type, i.e. biogenic calcite varves (Tylmann et al. 2013). Preservation of varves in the uppermost sediments was evaluated as excellent with very clear boundaries between individual laminae. The typical structure of these varves includes pale spring/summer lamina

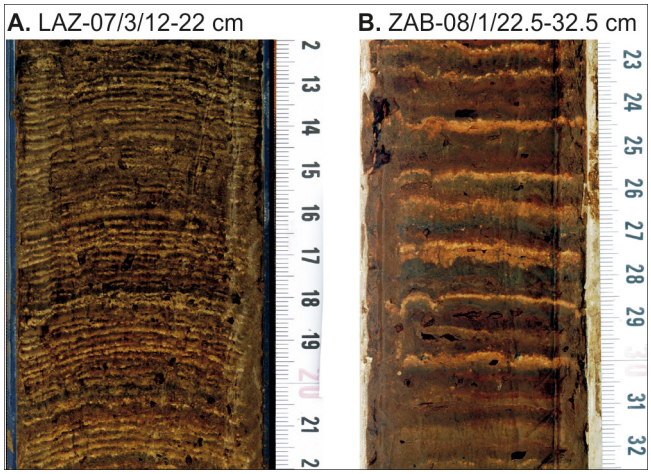

Fig. 5. Picture of topmost varves from Lake Łazduny (A) and Lake Żabińskie (B)

composed of autochthonous calcite crystals and dark fall/winter lamina made of organic detritus and minerogenic particles. However, as shown by microfacies investigations (Bonk et al. 2015a, b) in Lake Żabińskie these structures may be much more complex due to multiple calcite deposition during warm seasons. Detailed microscopic analysis of varves from lakes Łazduny and Rzęśniki is not available yet, but macroscopic inspection did not indicate such complex structures. Varve thickness (sedimentation rate) varies significantly between the lakes (Fig. 5). The topmost sediments of lakes Łazduny and Rzęśniki show fine laminations (2–3 mm yr^{-1}) while in Lake Żabińskie varves are very thick (4–10 mm yr^{-1}).

Conclusions and perspectives

Exploring the potential of varved lake sediments on an ultra high-resolution scale is a fascinating and novel scientific endeavor. However, it requires a much better understanding of lake systems, especially the relationships between meteorological conditions, catchment processes, limnological processes and sedimentation on short-term time scales. Process studies including monitoring of limnological parameters and particle fluxes offer insights into the structure and dynamics of these relationships. Moreover, a comparison of the reactions of different lake-catchment systems to the same forcing factors, e.g. meteorological conditions, will allow for establishing the sensitivity of different systems and their ability to archive such short-term environmental changes in the sediments.

Implementation of the outlined research will provide the scientifically sound information needed for a comprehensive interpretation of proxy records from lake sediments in northeastern Poland. The lakes se-

lected for this study contain well-preserved varves which makes them promising archives for reconstructions of environmental change. Differences between the catchment characteristics, hydrology and human impact provide an additional interesting aspect of potentially different reactions of these lakes to the same climate forcing. Comparisons of our results with similar monitoring systems in north-central Poland and northern Germany (ICLEA Project, Schwab et al. 2017), i.e. along the W–E climatic transect, would lead to regional synthesis which will further increase the value of the project.

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