2,400 yrs. climate and human-induced environmental change recorded in sediments of Lake Młynek in northern Poland

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Abstract

In the densily forested Warmia and Masuria region (northern Poland) there are many endorheic small lakes characterized by their low sedimentation rate, which makes them excellent archives of ~~the~~ Holocene environmental and palaeoclimatic change. Lake Młynek, located near the village of Janiki Wielkie, was selected for multi-faceted palaeoenvironmental research supported with radiocarbon dates. Sediments from this lake also contain unique information about human impact on the environment, because a stronghold has been operating on its northern shore since the early Iron Age to the early Medieval period, giving the opportunity to correlate palaeoenvironmental data with phases of the human activity over the last 2,400 years. During the 3rd and 2nd centuries BC the lake was surrounded by a dense deciduous forest. From the 1st century BC to 2nd century AD the forest around the lake was much reduced, which can be associated with the first pre-Roman (La Tene) and Roman occupation phase evidenced by the construction of the stronghold located close to the lake. From the 2nd up to 9th century AD gradual restoration of the forest and a decline of human activity took place, along with lake deepening and the onset of a colder and humid climatic phase which corresponded to the global cooling episode known as the Bond 1 Event (1.5 ka BP). The next intensive phase of forest clearing around the lake occurred between the 9th – 13th century AD as result of human activity (Middle Age settlement phase of the stronghold). This period is marked by a warming, which has impacted and transformed the landscape likely over prints any signals of climate-driven environmental changes.

Keywords: Late Holocene, lake sediments, Lake Młynek, environmental change, human impact, Iron Age, Middle Ages, northern Poland.

1. Introduction

Lake sediments are a useful source of proxies of past environmental and climate changes in the Holocene (see Brauer, 2004; Zolitschka, 2007; Wanner et al., 2008; Francus et al., 2013; Ojala et al., 2013; Welc, 2017). The main advantage of lakes for environmental reconstruction is the continuous and uninterrupted accumulation of their sediments. Well-dated lake sedimentary records allow for tracing of both long- and short-term climate changes in the Holocene (Smol et al., 2001; Tiljander et al., 2002; Valpola and Ojala, 2006; Czymzik et al., 2010; Elbert et al., 2012; Tylmann et al., 2012; Welc, 2017). Particularly valuable for palaeoclimate reconstructions are sequences from lakes without river inflow and outflow (Wetzel, 2001; Stankevica et al., 2015). As in most of Europe, many lakes in Poland have been heavily impacted by human activities within their catchments, resulting in many of them ~~to become~~ eutrophic in terms of their nutrient status (Cooke et al., 2005). Such intensive bio-productivity arising from nutrient enrichment results in the deposition of thick organic sedimentary sequences, mostly of organic gyttja composed of remains of aquatic plants, plankton and benthic organisms transformed by bacteria and mixed with mineral components supplied from the lake basin (Kurzo et al., 2004; Stankevica et al., 2015). There are ca. 1000 freshwater lakes of different sizes in the Warmia and Mazury Region in northern Poland (Fig. 1). Most of them are located within past glacial tunnel valleys formed by meltwater erosion at the termination of the Vistulian (Weichselian) Glaciation (ca. 115-12 ka BP). After deglaciation at the end of the Pleistocene these glacial tunnel valleys were partly filled with deposits and water, which persisted ~~to~~ the Holocene. Such lake basins have steep slopes and their bottom deposits are underlain by glaciofluvial sand, gravel and silt or glacial till (Kondracki, 2002; Gałązka, 2009). Many of these lakes are small (<1 ha), with stable sedimentation rates and without river inflow or outflow making them excellent sites for palaeoclimate reconstructions. Indeed, most of the climate reconstruction studies based mainly on pollen analysis are undertaken in this area (e.g., Kupryjanowicz, 2008; Kołaczek et al., 2013).

Lake Młynek is located near the village of Janiki Wielkie and it was selected for multi-faceted palaeoenvironmental research (pollen analysis, diatom, chrysophyte cysts, and geochemistry). It is hypothesized that the bottom sediments of this lake contain a unique record of human impact on the surrounding environment, as a result of the location of an Iron Age stronghold on the northern shore, which was active (though not continuously) up until the early Middle Ages (Fig. 1). Due to archaeological research stratigraphic units distinguished on this site were divided into seven main settlement phases: early Iron Age (I), stronghold abandoned after the early Iron Age (II), early Middle Ages (III), stronghold abandoned in the early Middle Ages (IV), settlement activity in the 11th – 13th centuries (V), stronghold definitely abandoned in the 14th century (VI) (Nitychoruk and Welc, 2017; Rabiega et al., 2017).

This study provides an opportunity to reconstruct the transformation of the vegetation around the lake that occurred under the influence of the climate (regional significance) and as a result of human activity. Our results were correlated with geoarchaeological data to determine mutual relations between environmental and climatic changes with development of human settlement phases in the Warmia and Mazury (northern Poland) region during the last 2,400 years.

2. Study area

Lake Młynek is a small water body that occupies a glacial tunnel valley since the Holocene. The lake is located in the Iława Lakeland in northern Poland, it is about 720 m long and 165 m wide. The lake has an area of 7.5 ha, with its water level at ~101 m a.s.l. and the maximum depth is just over 2 m. Lake Młynek is surrounded by a morainic plateau at 120-130 m a.s.l and its catchment ~~consist~~ is occupied by a dense forest (Fig. 1). In general, most of the Ilawa Lakeland is covered with forest (41.5%), whereas meadows and synanthropic communities have a smaller share. Among the habitats, a highly-productive mixed forest prevails. The basic components of the Iława forest are pine (*Pinus*), oak (*Quercus*), beech (*Fagus*), alder (*Alnus*), birch (*Betula*), in smaller amounts there are spruce (*Picea*), larch (*Larix*), ash (*Fraxinus*), hornbeam (*Carpinus*), maple (*Acer*) and linden (*Tilia*). Currently, the lake sits in a catchment that is characterized by a transitional climate with influence of continental and maritime circulation. The growing season lasts about 206 days, and the snow cover remains for 70-90 days. Average temperature values range from approximately -4.0°C in February to above 17.0°C in July. Due to significant participation of the polar air masses and a large number of natural water reservoirs, air humidity is relatively high, ranging from 72% to 89%. Total annual precipitation ranges from 500 to 550 mm a year. Southwestern winds dominate throughout a year, with westerly winds stronger in winter and the highest wind speeds recorded during the winter months (Jutrzenka-Trzebiatowski and Polakowski, 1997; Stopa-Boryczka at al., 2013). It is important to note, that from the north, a small stream flows into the lake Młynek, which is active in winter and dries up almost completely in summer (Fig. 1: D). The stream is a result of irrigation related to the construction of a mill in the 15th century, somewhere in the vicinity of the medieval stronghold located on the northern shore of the lake (Semrau, 1935, Bińka et al., 2020).

3. Material and methods

3.1. Bathymetry

Determination of lake bathymetry and thickness of bottom sediments is extremely important in palaeolimnological research to help locate appropriate coring sites. This can be achieved through the use of GPR sounding (Lin et al., 2009; Sambuelli et al., 2009; Sambuelli and Silvia, 2012). In Poland winter is a particularly convenient season when the lake is covered with ice, making GPR profiling much easier and improving access and speed of data collection (Hunter et al., 2003). Measurements along and across the lake were carried out in 2017, directly on the lake ice (Fig. 2). We used the radar system ProEx of the Malå Geoscience (www.malagpr.com.au/mala-professional-explorer.html). A radar pulse was generated at a regular distance interval of 0.02 m (900 samples were recorded from a single pulse). The time window of recording was between 250 and 300 ns. Prospection was done with use of a shielded monostatic antenna with 250 MHz nominal frequency of the electromagnetic wave.

3.2. Coring and sampling

Based on the results of the GPR sounding,4 drillings were undertaken a ca. 2 m water depth (Fig. 3) ~~to collect cores~~ following the Givelet et al. (2004) collecting protocol. A piston sampler was used during drilling, which is very suitable for sampling in moderately cohesive sediments to a depth of 5 m. The sampler set consists of a 200-cm long sonde, which is constructed from a thin-walled, 40-mm diameter, stainless steel tube (https://en.eijkelkamp.com/products/sediment-samplers/Piston-Sampler-set.html). Sediment cores were film-wrapped in 1 m plastic tubes and transported to the laboratory. The cores (M1-4) were then subjected to magnetic susceptibility measurements which enabled the selection of the core M-1, the longest and most continuous, to carry out detailed analysis. The 3.5 m long core M-1 (geographic coordinates: 53.82486 N, 19.72419 E) was sub-sampled at 5 cm intervals and used for multi-proxy laboratory analyses.

3.3.Magnetic susceptibility (MS)

The cores from Lake Młynek were subjected to MS measurements using SM-30 magnetic susceptibility meter (ZH Instruments). Due to very high sensitivity (1 x 10^{-7} SI units) this device was provided with 8 kHz LC oscillator and its pick-up coil sensor was large enough to measure sufficiently high volume of sediments with very low MS. The measurements were done at every 5 cm along each core (M1-4).

3.4. Radiocarbon dating and age depth model

Radiocarbon dating was performed on 4 bulk samples from the core M-1, collected either from organic-rich gyttja or gyttja with dispersed organic matter (Table 1). The organic matter seems to have been derived both from aquatic and terrestrial sources. AMS dating was carried out by the Poznań Radiocarbon Laboratory in Poland (for methodology see Goslar et al., 2004). The construction of age-depth models required an assessment of several factors that could disturb constant accumulation of bottom deposits of Lake Młynek, such as those from sedimentary and post-sedimentary processes (including a varied rate of deposition and compaction, and the impact of bioturbation). The varied influx of material delivered to the lake from the adjacent area is a very important factor of disturbance. Therefore, a Bayesian age-depth model was chosen as it takes into account the sedimentation rate and its variability (Blaauw and Christen, 2005, 2011; Blaauw et al., 2007) (Fig. 4). The model was based on default settings, except for section thickness which was set at 0.05 cm given the length of this core. The Bacon model uses the IntCal3 curve (Reimer et al., 2013) to calibrate the radiocarbon data.

Table 1. List of radiocarbon determinations.

No.	Depth in m	Lab. reference	^{14}C yr. BP	Age calibrated 95% probability	Material dated
1	0.95-1.00	S/JW 1/2015/A	435 ± 30	1418 – 1494 AD	Bulk of gyttja
2	1.65-1.70	S/JW 1/2015/B	1015 ± 30	971 – 1048 AD	Bulk of gyttja
3	2.40-2.45	S/JW 1/2015/C	1730 ± 30	236 – 386 AD	Bulk of gyttja
4	3.45-3.50	S/JW 1/2015/D	2275 ± 30	401 – 351 BC	Bulk of gyttja

3.5. Palaeobotanical analysis

3.5.1 Pollen

The core M-1 was sampled every 5 cm for pollen analysis. 70 samples (ca. 10 g each) were treated with 5% HCl, boiled in 5% KOH and hot 30% HF. They were washed with 15% HCl and treated by the standard Erdtman's acetolysis. In each sample about 1000 pollen grains were counted using an optical microscope at 400x magnification.

3.5.2 Diatom and Chrysophyte cysts analysis

70 samples were prepared for the analysis of diatoms and chrysophyte cysts. They were extracted from 1 g of dry sediment ~~of each sample~~ using the disintegration method in HCl and H_2O_2, according to the technique proposed by Zalat and Servant-Vildary (2007). For slide preparation, 0.1 ml of the final suspension was dried on coverslips and then mounted onto slides using Naphrax. Diatoms were identified to species level using a Leica photomicroscope with a digital camera and equipped with differential interference contrast (DIC) optics at 1000x magnification with oil immersion. Identification and ecological information of the diatom species were based primarily upon the published literature (e.g. Kilham et al., 1986; Douglas and Smol, 1999; Witkowski et al., 2000; Hofmann et al., 2011). Recent taxonomic advances split many diatom taxa of the former genus *Fragilaria sensu lato* into several new genera, including *Fragilaria*, *Pseudostaurosira*, *Staurosira* and *Staurosirella* spp. (Williams and Round, 1987); these new names herein collectively referred to as *Fragilaria sensu lato*. Chrysophyte cysts were described and enumerated following Duff et al. (1995, 1997), Pla (2001) and Wilkinson et al. (2002). Preliminary results of the diatom studies based on the core M-1 were already published by Zalat et al. (2018).

3.6. Geochemical analysis

ICP-OES spectrometer was used for determination of basic (Al, Ca, Mg, Na, K, Fe, P) and trace elements (As, Cd, Mn, Th, Ti, U, V, Zn). Powdered samples were mineralized in a closed microwave Anton Paar Multiwave PRO reaction system. Mineralization procedure was based on the procedure of Lacort & Camarero. Characteristics of lake sediments were determined by the extraction method of elements that are soluble in aquaregia (according to European Standard CEN/TC 308/WG 1/TG 1, slightly modified). Dry samples of about 0.2 g weight were transferred to the PTFE vessel and HNO_3, and HCL Merck Tracepur® was added. The vessels were placed in a rotor and loaded to a microwave. Finally, the samples were analysed in the Spectro Blue ICP

OES spectrometer at Regional Research Centre for Environment, Agricultural and Innovative Technologies, Pope John II State School of Higher Education in Biała Podlaska. Berndt Kraft Spectro Genesis ICAL solution and VHG SM68-1-500 Element Multi Standard 1 in 5% HNO_3 were used.

Total organic carbon (TOC) analysis was done after sample acidification to remove carbonates in the SHIMADZU SSM 5000A analyser with a solid sample combustion unit. The method was the catalytically aided combustion oxidation at 900°C with pre-acidification and oven temperature 200°C. A measuring range TC was 0.1 mg to 30 mg carbon. Sample amount was 1 g and aqueous content <0.5 g. Repeatability: S.D. ±1% of full-scale range (www.ssi.shimadzu.com/products/toc-analyzers/ssm-5000a).

All selected samples were analysed using a scanning electron microscope (SEM) HITACHI TM3000 with an energy dispersive spectrometer (EDS) SWIFT ED 3000 Oxford Instruments. The samples were not covered with any conductive material. Magnification range was x 20 to x 30 000. This method was used to perform basic microscopic observations of samples of the core M-1 with point determination of their chemical composition of major elements.

4. Results

4.1 Bathymetry

A georadar transect across the lake reflects both its bathymetry and composition of its bottom (Figs 2 - 3). The superficial layer of the transect is represented by lake ice, ca 25 cm thick and although it is almost not visible on radar images due to its thickness being smaller than a vertical resolution of measurements, beneath there are abundant horizontal multiple reflections of energy from the bottom of the ice. Two narrow and vertical zones with small diffraction hyperboles at 23 and 29 m of the transect indicate upward deformation of bottom sediments at the location sites of the sounding core and the core M-1 (Fig. 2a). The top of the underlying mineral deposits (so-called hard bottom) is indicated as a distinct downward-deflected reflection surface (Fig. 2b). In the central part of the lake, it occurs at 2.6 m depth (two-way travel time 290 ns) and indicates the top of the Holocene organic sediments. Unfortunately, beneath there is a signal-absorption zone (Fig. 2d), resulting from the fact that most sediments are composed of fine-grained organic material (gyttja). However, thickness of this layer was determined by drillings to about 5 m. A relief of the lake bottom in the GPR image reflects a cross-section of a buried glacial tunnel valley that was eroded mainly in sandy and sandy-gravel deposits. Close to the lake shore (0 to 20 m in the northwest and 110 to 140 m in the southeast), there are numerous oblique and chaotically parallel reflection surfaces dipping towards the channel axis. They reflect bedding of the Pleistocene sandy-gravel series that partly filled a subglacial channel (Fig. 2c).

4.2. Magnetic susceptibility

MS is highly dependent on lithology and grain size of deposits (Dearing, 1994; Sandgren and Snowball, 2001). It reflects presence and size of ferromagnetic particles in a sample (Verosub and Roberts, 1995). Increased content of ferromagnetic minerals such as magnetite, Fe-Ti oxides or pyrrhotite generates higher MS whereas biotite, pyrite, carbonates and organics result in its lower values. Total volume of magnetic minerals in lake sediments reflects mostly climatic changes in a catchment (Bloemdal and deMenocal, 1989; Snowball, 1993; Peck et al., 1994). MS in the core M-1 is varied but due to organic character of the sediments, its values are relatively low, from 0.002 to 0.034×10^{-7} units SI. In grey-brown gyttja with organic matter at 3.50 – 2.58 m depth, MS rises and drops in turn from 0.01 to 0.02×10^{-7} SI. MS drops from 2.60 m depth, reaching a minimum at 1.63 m. Higher up, MS rises again, with the highest value at 1.35 m, then there is a minimum at 1.05 m and the next maximum at 0.69 m depth (Fig. 6).

4.3. Chronology, lithology and sedimentation rate

The age-depth model of the core M-1 from Lake Młynek indicates (Fig. 4) that the M-1 core chronologically covers the last 2,400 years. Bottom deposits of Młynek Lake are organic-rich. The core M-1 is composed of grey-brown gyttja at 1.8 – 3.6 m depth (Fig. 5). At 1.45 – 1.80 m depth there is grey-brown gyttja-detritus and at 1.10 – 1.45 m depth algal gyttja is recorded. The uppermost part of the core is composed of grey-brown (depth 0.4 – 1.1 m) and detritus gyttja (0.0 – 0.4 m). The sedimentation rate was calculated based on the age-depth model. Results reflect quite a stable sedimentary environment with a general rate of 1.5 mm a year. The rate is stable at 3.40 – 1.77 m depth and equal ca 1.5 mm a year. It drops to 1 mm, then rises to 1.3 – 1.8 mm a year at 1.77 – 0.30 m. At 0.0 – 0.3 m the sedimentary rate is the highest and equal ca 3 mm a year (Fig. 5).

4.4. Pollen

Based on percentage contents of main trees and terrestrial herbs five local pollen assemblage zones (LPAZ M1-M5) were established in the pollen sequence of the Lake Młynek. The pollen contents were determined based on changes in the percentage of individual taxa, confirmed by a cluster analysis (Fig. 9):

Zone	**Depth [m]**	**Main features of pollen spectra**
LPAZ M-1	345÷315 cm	Pollen grains of *Carpinus* reached 33.5% and *Alnus* 25%, *Pinus* and *Betula* are <20%. A top border of this zone is indicated by decline of *Carpinus.*
LPAZ M-2	315÷265 cm	The share of *Carpinus* drops significantly (<10%), contents of *Betula*, *Quercus* and *Corylus* are slightly raised. The percentages of Gramineae significantly increased up to 7.5%. There are continuous curves of *Cannabis/Humulus,* Chenopodiaceae, *Plantago lanceolate, Rumex acetosella* and *Secale cereale* and a top boundary is indicated by decline of Gramineae.
LPAZ M-3	195÷265 cm	At the beginning the curve of *Betula* raises to 24% but then drops <10%. The share of *Carpinus* and *Fagus* rises to 19% and 27%, respectively. Content of Gramineae decreased <2% and the curves of *Secale cereale, Plantago lanceolate* and *Rumex acetosella* disappear. There are only single pollen grains of Chenopodiaceae and C*annabis/Humulus.* A top boundary is indicated by a rise of Gramineae.
LPAZ M-4	195÷145 cm	Content of *Fagus* pollen began gradually decrease. The share of pollen grains of *Betula* increases and becomes stable at 22-27%. Content of the Gramineae pollen grains increases again to 7%. Curves of *Cannabis/Humulus, Plantago lanceolate, Rumex acetosella* and *Secale* raise and a top boundary is marked by a rapid rise of *Cannabis/Humulus.*
LPAZ M-5	145÷15 cm	Curves of main deciduous trees decline: *Carpinus* <9%, *Fagus* <5%, *Quercus* <5%, *Alnus* <15%, *Betula* <14% and content of *Pinus* increases to 40%. There is significant rise of Gramineae up to 15%. Percentages of *Cannabis/Humulus* reached absolute maxima (25%) but close to middle part of this zone their strong decline is observed (below 2-3%). The continuous curves of *Cerealia* undiff., *Centaurea cyanus, Plantago lanceolate, Rumex acetosella, Rumex acetosella* appeared, and single pollen grains of *Polygonum dumetorum, Polygonum aviculare* and *Urtica* were present.

4.5. Diatoms

Studies of the Lake Młynek bottom sediments revealed presence of more than 200 diatom taxa belonging to 54 genera (Zalat et al., 2018) (Fig. 8). Diatoms were generally abundant and well to moderately preserved in most samples, although with admixture of mechanically broken valves, especially in the topmost part of the core. Results of the diatom analysis and relative abundance of the most dominant taxa enabled subdivision of the M-1 core section into 11 diatom assemblage zones (Fig. 8) that reflected six phases of lake development (Zalat et al., 2018). Moreover, changes in chrysophyte cysts distributions along with variation in diatom composition could be related to changes in pH, climate and trophic status. Stomatocysts can be used as the index of lake-level changes, habitat availability, metal concentrations and salinity.

4.6. Geochemistry

Various factors influence distribution and accumulation of geochemical elements in lake sediments. Most important are texture, mineral composition, oxidation/reduction state, absorption/desorption and physical transportation processes (Ma et al., 2016). Curves of representative elements are generally used to characterize sedimentary environments. Most analysed elements do not indicate any clear trend with depth in the Lake Młynek. The curves of S and TOC show significant rises at 2.0 – 1.4 m depth that are slightly correlated with decreased contents of Al, Fe, K, Ca, Mg and MS (Fig. 6). Sulphur content is correlated with existence of iron sulphides. In the studied core, Fe is positively correlated with Al and Ti (Fig. 7). Fe-Ti oxides are noted in SEM EDS analysis. They are resistant to surface weathering and carry trace elements (Bauer and Velde, 2014). At ca. 3 m, high frequency peaks of Al, K, Ca, Na, Mg, Fe and S occur (Fig. 6).

5. *Discussion*

MS is generally low in biogenic sediments as gyttja, which is composed mainly of microfossil skeletons e.g., diatoms and radiolarians (Thompson and Oldfield, 1986). In Lake Młynek there is an apparent negative relationship between TOC and MS. Several intervals show both higher percentages of TOC and lower MS values. Changes of MS in Lake Młynek sediments ~~record~~ most probably an input of clay into the lake and diagenetic conditions in bottom sediments. Iron oxides are presumably of detrital origin and were delivered to the basin through deep valleys incised at the north-western shore. Concentration of ferromagnetic minerals is connected with periodical intensive soil erosion around the lake. Their higher content depends also on diagenetic processes in bottom sediments. Oxidation of organic matter in anoxic conditions (by iron-oxide-reducing bacteria) results usually in increased content of ferromagnetic particles (small particles are removed first). In opposite, oxygenation by heavy floods stops this process and small magnetic particles are preserved (Jelinowska et al., 1997). At 1.40 m depth, TOC suddenly drops, probably due to deforestation and then, MS significantly rises due to increasing input of terrestrial (nonorganic) material to the lake. Such coincidence clearly indicates that TOC is both of autochthonous and allochthonous derivation (Fig. 6).

The highest content~~s~~ of detrital elements like Al, K, Ca and Mg are ~~to be~~ associated with sudden delivery of clastic material to the lake e.g. during increasing flood or rainfall (Wirth, et al., 2013). ~~Especially~~ Al is extremely immobile, that is why it should be regarded as a typical lithogenic element (Price et al., 1999). Additionally, Al is a major constituent of soils and other sediments as a structural element of clays. It has a strong positive correlation with many major elements (Fig. 7). The association between Al and other elements can be therefore used as the basis to compare natural elemental contents in sediments and soils. Ca is well correlated with Al, ~~originated mainly~~ from terrigenous bicarbonate inputs and ~~was~~ deposited in a lake as a solid carbonate (Miko et al., 2003). Calcium is evidently more easily removed in solution from a mineral material and it is highly concentrated in highly erosional periods (Mackereth, 1965).

The Fe/Ca ratio is considered as a eutrophication proxy. The highest ~~ratio points out~~ to low oxygenation, eutrophic or dystrophic reservoirs (i.e. Kraska and Piotrowicz, 2000; Holmes and De Decker, 2012), whereas the low Fe/Ca ratio in bottom sediments indicates oligotrophic character of a lake. In the studied core sediments, Fe/Ca ratio varies from 0.808 (depth 3.05 m) to 3.677 (1.2 m). The ratio is low, indicating oligotrophic conditions in bottom sediments which gives conflicting results with other data. The Fe/Ca ratio can be disturbed by detrital input to the lake (Fig. 6). The dysaerobic conditions in the lake are confirmed with Th/U ratios (0.03 – 0.41) which are lower than the critical value of 2 as indicated by Myers and Wignall (1987) and Wignall (1994). The ratio of total Fe to total P ranges from 13.91 (1.6 m depth) to 30.82 (0.55 m). The values are typical for other lakes in northern Poland, which vary from 3 to 180 according to Bojakowska (2016). The release of P follows ~~in~~ reducing conditions. According to Ahlgren et al. (2011) is even up to ten times greater than in aerobic conditions. However, there is a poor correlation with other redox proxies i.e. Th/U (R=0.08). It can be caused by presence of Al which forms $Al(OH)_3$. In such systems even though the redox state favours release of P from iron minerals, the P is immobilized by binding with hydroxides. Thus, the presence of $Al(OH)_3$ can stop release of P even in an anoxic hypolimnion (Hupfer and Lewandowski, 2008). ~~It can be a~~ case in the studied sediments as Al shows positive correlation with P content (R=0.49). Except for Fe/Ca, all counted ratios point ~~out~~ to anoxic conditions in all studied samples which is typical to eutrophic lakes. Nevertheless, as all proxies are characterized by extreme values at the 3.05 m depth, they seem to depend on external load of terrigenous material. It is confirmed with very good positive correlation between Fe and Al (0.95), Fe and Ti (0.64) Mn and Al (0.46) or Mn and Ti (0.78).

The periphytic diatom species dominate ~~the planktonic ones~~ throughout the core. A high proportion of periphyton to plankton assemblages was reported as indicative for a long-lasting ice-cover (Karst-Riddoch et al., 2005) whereas a shift from benthic to planktonic diatom taxa is considered ~~for~~ an ecological indicator that is ~~generally~~ interpreted in high-altitude lakes as record of shorter winter and increased in temperatures. Common occurrence of benthic forms represented by *Staurosira venter*/*Staurosirella pinnata* diatom assemblage indicates circumneutral to slightly alkaline shallow water with lowering lake levels and prolonged ice cover. However, *Aulacoseira* is the most dominant planktonic genus followed by *Cyclotella* and low frequency of *Cyclostephanos*. Diatom preservation in the upper part of the core (depth 1.40 – 0.15 m) is moderate to relatively poor and the recognized assemblage was represented by the occurrence of some dissolved and teratological diatoms valves, in particular the topmost part of the core section (0.30-0.15 m) (Zalat et al., 2018).

6. Phases of the Lake Młynek development

Based mostly on results of palynological studies five main phases of the Lake Młynek development in relation to the climate and human-induced environmental change were distinguished (Fig. 10):

5.1. Phase 1: 2,300 – 2,100 cal. BP (ca. 4 – 2/1 c. BC), depth: 3.45 – 3.15 m

This phase is recorded in LPAZ M-1 which represents closed forest communities dominated by hornbeam and alder, which colonized marshlands near lake shores. Plants of open stands are only rarely noted as well as indicators of anthropogenic activity (e.g. *Plantago lanceolata*). Vegetation at that time was relatively natural and not disturbed. Diatom assemblage at the ~~beginning~~ (3.45 – 3.40 m depth) was distinguished by diatom subzone DZ1a (Fig. 8) ~~that dominant~~ by ~~the~~ periphytic taxa such as *Staurosira construens, Staurosira venter, Staurosirella pinnata, Gyrosigma acuminata* associated with the planktonic *Aulacoseira granulata, A. ambigua* and *Puncticulata radiosa* which indicates a shallow and slightly alkaline lake. This interval was followed by a great abundance of the planktonic alkaliphilous diatoms of subzone DZ 1b (3.35 – 3.15 m, fig.8) ~~which was dominant~~ by *Aulacoseira granulata, Cyclotella sensu lato* species, *Cyclostephanos dubius* and *Stephanodiscus* species. The diatom assemblage ~~explains~~ a rising lake level with increasing nutrients ~~matter~~ (Douglas & Smol 1999, Zalat 2015). The predominance of *A. granulata* suggests a high trophic status ~~of~~ slightly alkaline freshwater environment with high silica concentration (Kilham et al. 1986; Zalat et al., 2018). MS is high and corresponds to high contents of Fe, Ti and Al, indicating increasing influx of terrigenous material, presumably activated by intensive rainfall~~s.~~

5.2. Phase 2: 2,100 – 1,830 cal. BP (ca. 1 c. BC – 2 c. AD), depth: 3.15 – 2.65 m

During this phase ~~2~~ changes in the environment around the lake were caused by significant human impact. This phase corresponds with the LPAZ M2, characterized by reduction and fragmentation of the hornbeam-dominated forest. Birch, pine and hazel expanded under better lighting conditions in a partly open forest. Mid-forest pastures occupied rather small-scale open areas, as can be ~~notified~~ from higher percentages of *Plantago lanceolata* and other herbaceous plants, e.g. Gramineae, *Artemisia* and *Rumex acetosa*/*acetosella*. Cultivated plants as *Cannabis* t. and *Secale* are rare, however their occurrence is entirely consistent with other human indicators present during this phase. This phase is commonly noted and similarly expressed in numerous palynological sequences in neighbouring areas (see for example Noryśkiewicz, 1982, 1987, 2013; Bińka et al., 1991; Ralska-Jasiewiczowa et al., 1998). Pollen data indicate that societies of that time cultivated rye and probably hemp. It is the oldest settlement phase at Janiki Wielkie stronghold and corresponds to the termination of the La Tène and the time of the early Roman period. Human communities in the vicinity of the lake can be connected with settlements of the East-Baltic Kurgan Culture (Rabiega et al., 2017). During this phase, planktonic diatoms were replaced by benthic taxa, (DZ2) such as *Staurosira construens, S. venter,* and *Staurosirella pinnata* accompanied by a significant abundance of *Gyrosigma acuminatum* indicating a lower lake level and dominance of mesotrophic alkaline freshwater environment. The lower stands were interrupted by a short rise of water level at 2.90 – 2.85 m where the abundance of planktonic eutrophic indicator *Aulacoseira* spp. increased suddenly on expense of the benthic taxa. During this phase climatic conditions were still similar to ones in the previous phase, but it was drier ~~what~~ is reflected by shallowing of the lake. This phase can be correlated with the so-called Roman Climatic Optimum (see McCormick et al., 2012).

5.3. Phase 3: 1,830 – 1,150 cal. BP (ca. 2 – 9 c. AD), depth: 2.65 – 1.95 m

This phase corresponds to LPAZ M3 when ~~a~~ forest restoration occurred. Absence of human indicator plants suggest that the settlement in the catchment was abandoned. There are also no traces of human activity nearby (Rabiega et al., 2017). Reduction of human impact and human-generated semi-open habitats, allowed for a short-term expansion of birch into empty, open areas, and later replaced by hornbeam that rebuilt its position to the level as in the LPAZ M1. ~~Also,~~ elm expanded again in a riparian forest. This restoration of the natural forest was followed by abrupt expansion of beech in the second half of the LPAZ M3. The area of open herbaceous plants communities, previously widespread, was limited.

Abundant planktonic diatoms including *Aulacoseira* spp., *Puncticulata radiosa*, and common occurrence of small *Cyclotella* spp. occurred in the lake (Fig. 8) ~~what~~ indicates its deepening, enhanced thermal stratification, reduced mixing and increased thermal stability (Zalat et al., 2018). Intensified development of ~~a~~ vegetation cover and higher lake ~~water~~ level are indicated by geochemical indices. A gradual drop ~~of~~ MS corresponds with decreased content of detrital elements ~~as~~ Fe, Ti, Al and K, accompanied by gradual increase of TOC and the ~~proxy~~ ratio ~~Fe/Ca~~. Lower MS and content of Al (acting as a major constituent of soils) accompanied by the higher TOC suggest limited erosion~~,~~ in spite of gradually higher precipitation in the lake catchment and therefore, a rise ~~of~~ its water level (Fig. 6). The climate in this phase has become more humid. Increased rainfall and decreased evaporation are reflected in lake sedimentation as the lake got deeper, resulting in reduced deposition and greater stability. This phase could be associated with a global cooling of the Bond Event 1 (1.5 ka BP) (Bond et al., 1997; Welc, 2019).

5.4 Phase 4: 1,150 – 780 cal. BP (ca. 9 – 13 c. AD), depth: 1.95-1.45 m.

This phase is correlated with the LPAZ M4 and ~~was~~ divided into two subphases 4a and 4b (Fig. 10). The ~~subphase~~ 4a marks the onset of another settlement phase, resulting in forest clearing, ~~similarly as in the LPAZ M2.~~ Disturbances took place firstly in a beech forest and less in a hornbeam-dominated one. The anthropogenic activity is reflected by presence of *Gramineae, Artemisia*, *Cannabis*/*Humulus*, *Plantago lanceolata*, *Rumex acetosella*, *Secale* and cerealia undiff. Diatom assemblages ~~proves~~ deepening of the lake (Zalat et al., 2018) as indicated by abundance of *Aulacoseira* associated with *Puncticulata radiosa* in the upper part of the diatom zone 5 at 1.85 – 1.70 m depth. The diatom assemblage suggests a rising lake level, higher trophy and stronger turbulent mixing conditions (Rühland et al., 2008; Zalat et al. 2018). Moreover, the greatest reduction of abundant *Fragilaria sensu lato* accompanied by abundant *A. granulata*, could ~~resulted~~

from forest clearing around the lake. Higher TOC corresponds with lower content of detrital material (Fe, Ti, Al and K) and lower MS, and it can reflect a progressing humidity (Fig. 6). This phase can be correlated with the Migration Period and the early Middle Ages. A wooden-loamy defence rampart was raised at the end of the phase in a settlement close to the lake (archaeological phase III), after removal of ~~a~~ natural soil developed during abandonment of the site in the early Roman Period. After a short period, this stronghold was destroyed. ~~A~~ charcoal from a fired wall that represents destruction at the end of the archaeological phase IIIA, was dated ~~at~~ 1245 ± 25 cal. BP i.e. 682-870 AD (95.4% probability) and 1090 ± 30 cal. BP i.e. 892-1014 AD (95.4% probability) (Rabiega et al., 2017).

Human impact declines during the subphase 4b (1.70 – 1.45 m depth) ~~onwards.~~ At this time birch and ~~less intensively~~ poplar occupied temporarily abandoned open areas, especially toward the end of the zone, when a human activity was less intensive. Alder became more abundant, probably expanding into exposed marginal areas of the lake. The subphase 4b, corresponds to ~~the~~ diatom zone 6 (Fig. 8) which is characterized by abundant benthic *Fragilaria sensu lato* with sporadic occurrence of planktonic taxa. A high proportion of benthic to plankton assemblages was reported as indicative for a long-lasting ice-cover (Karst-Riddoch et al., 2005). As well as, a great abundance of the benthic *Staurosira venter* and *Staurosira construens* with marked decline in the planktonic diatoms such as *Aulacoseira* spp. and *Puncticulata radiosa* reflects lowering water level and slight alkaline freshwater, lower nutrient concentrations and low silica content (Kilham et al. 1986; Stevens et al., 2006; Zalat et al., 2018).

In the stronghold at the lake shore, the next phase of human activity took place at the end of the 11th century AD when a new rampart was raised. Wooden constructions were also built, traces of which were excavated in the gate passage. The settlement was finally abandoned presumably in the first half of the 13th century and then~~,~~ its ramparts were strongly eroded, with their material moving towards a yard and the moat (Rabiega et al., 2017). The subphase 4b is characterized by ~~climate change towards~~ a gradual warming, which ~~confirms~~ gradual shallowing of the lake and increased rate of sedimentation. Human impact on the environment in this subphase is already so great that reconstruction of a climate change is not clear. There is no doubt, however, that this is a warm period, which should be correlated with the Medieval Warm Period (MWP) (Mann et al., 2009).

5.5. Phase 5: 780 – 0 cal. BP (13 c. AD – present time), depth: 1.45 - 0 m

This phase starts about 1200 AD and is connected with the early Modern Period. Cultivation and treatment of hemp has been terminated but cultivation of cereals and presence of synanthropic plants indicate human activity near the lake. The water level is not high and slightly changes, which is ~~evident~~ by ~~great~~ abundance of ~~the~~ benthic diatom taxa over the planktonic forms (DZ 8-10, fig. 8). There is a drop ~~of~~ TOC and rise ~~of~~ MS caused by increasing input of terrestrial material at 1.4 m depth, resulting presumably from human deforestation. The small watercourse which enters the lake from the north–east appeared most probably during this phase and had a strong impact on the its water environment (see, Bińka et al, 2020). As ~~it was mentioned before~~, in 15 ~~c.~~ AD a mill was built near the lake and damming of the water in the mill reservoir probably contributed to periodical blooms of dinoflagellate populations in Lake Młynek. Major blooms of *Tetraedron* which usually precede blooms of the dinoflagellate, were most probably the main factor that contributed to the decline of settlement ~~on~~ the stronghold ~~near the shore of the lake~~ (Bińka et al, 2020). This zone is also characterized by increased precipitation which is reflected by ~~significantly~~ more intensive terrestrial inflow to the lake and is confirmed by quasi-linear correlation of MS with contents of Fe and Ti in sediments (Fig. 6). The modern lake is shallow (2-3 m) and gradually overgrowing. Summing up, the phase 5 is marked by intensive human activity around the lake and therefore, most environmental and climate changes are obliterated.

7. Development of Lake Młynek – a regional background

The above scenario seems to be confirmed by earlier palaeoenvironmental research carried out in the south-western part of the Warmia-Masuria Lakeland (Kupryjanowicz, 2008; Kołaczek et al., 2013). Previous studies of the lakes sediments in this region were based mainly on pollen analysis and enable ~~to compare~~ Lake Młynek record with other sequences.

The closest Lake Woryty (Pawlikowski et al,.1982, Noryśkiewicz and Ralska-Jasiewiczowa, 1989, Ralska-Jasiewiczowa and Latałowa, 1996), just 35 km to the east, is a reference one. Palaeoenvironmental records ~~delivered by~~ Lake Młynek core are very similar to the Woryty palynological succession with distinctive human impact during the Roman Period and the Medieval Ages, however, a detailed comparison is difficult, because of the low resolution of the pollen spectrum obtained at Woryty.

The second site is Lake Drużno, located in the Vistula Delta, 35 km to the north of Młynek Lake (Zachowicz et al., 1982; Zachowicz and Kępińska, 1987; Miotk-Szpiganowicz et al., 2008).

Unfortunately, the low resolution and the lack of reliable age-depth model of the lake comparison ~~also very~~ difficult. Despite ~~of this and also due to~~ habitat differences between Lake Drużno and Lake Młynek, pollen records obtained at both sites are very similar and comprise human indicators during the Roman Period and human impact during the Medieval time.

The pollen spectrum from Lake Łańskie (Madeja, 2013), located 55 km to the south-east from Lake Młynek, shows higher content of pine and lower share of beech than in the case of Lake Młynek. Such divergences are probably not only due to different location and environmental conditions in the lake vicinity but also depend on different size of these lakes. Lake Młynek is a very small (0.7 km^2) mid-forest basin, whereas Lake Łańskie is over 10 km^2 large and contains mostly a regional pollen record. Based on periodical appearances of human plant indicators and archaeological data between 300 BC and 800 AD, three human phases of West Baltic Barrow, Wielbark and Prussian cultures were distinguished (Madeja, 2013). In the pollen diagram from Lake Młynek (phase 2), the first culture is indicated, including termination of the La Tene and the Roman Period. Significant growth of human indicators from the beginning of 11th century ~~is~~ visible in diagrams from both sites. A more local record from Lake Młynek is marked especially by high content of *Humulus*/*Cannabis* (to 25%) in 13-15th centuries AD. In the sediments of Lake Łańskie, hemp occurred discontinuously and was <1%.

The pollen records from Lake Młynek are similar to the ones from the Masurian Lakes: Wojnowo, Miłkowskie and Jędzelek, located over 100 km to the east (Wacnik et al., 2014). Recorded episodes of human impact on vegetation during the Roman Period and Medieval time are separated by 500-600 years long intervals without cultivation and with natural reforestation (indicated by strong ~~share of~~ birch which is a pioneer ~~tree)~~. ~~Similar lasting~~ of human withdrawal in the Lake Młynek section began and terminated earlier than recorded in the lakes Wojnowo and Miłkowskie. Another history of human activity is represented in a record from Lake Salęt (Szal et al., 2014b). Pollen grains of cultivated and ruderal plants are noted continuously from the early Iron Age to the early Medieval time. In ~~opposite~~ to the pollen record from ~~the~~ lakes Młynek, Wojnowo and Miłkowskie, the suggested ~~constant~~ settlement in the neighbourhood of the Lake Salęt was interrupted by a single very short decline of human impact ~~at~~ 880-980 AD (Szal et al., 2014a). Numerous pollen data are available from the area adjacent in the south-west in the Brodnica Lake District, including Strażym Lake (Noryśkiewicz, 1987; Noryśkiewicz and Ralska-Jasiewiczowa, 1989), Oleczno Lake (Filbrandt-Czaja, 1999; Filbrandt-Czaja et al., 2003) and the

Chełmno Lakeland (Noryśkiewicz, 2013). Pollen records from this region also suggest intensive settlements during La Tene, Roman and Medieval periods.

Pollen record from other sites located to the east of Lake Młynek ~~indicates mostly~~ differences in ~~a beech content~~. The *Fagus silvatica* content changes to the north-east and its significantly high content in Lake Młynek sediments represents a very local record in a small lake. Decline of *Fagus sylvatica* depend on a continental climate and is noted in pollen diagrams from the lakes: Salęt (Szal et al., 2014a), Mikołajki (Ralska-Jasiewiczowa, 1989), Żabińskie (Wacnik et al., 2016) and Wigry (Kupryjanowicz, 2007). A decline of beech is accompanied by a rise of *Picea abies*. A record of human activity in pollen spectra from eastern Poland was noted at many sites.

8. Conclusions

Based on results of performed laboratory analysis, supplemented with archaeological data, five main environmental phases of the Lake Młynek development were distinguished (Fig. 10). Radiocarbon ages enabled detailed chronology whereas pollen data and stratigraphy of the stronghold to the north-east of the lake made correlation of human activity with environmental data possible for the last 2300 years. From the 1st century BC to 2nd century AD the forest around the lake was much reduced, ~~what can be~~ associated with pre-Roman and Roman occupation phase (attested also on the stronghold located close to the lake). From the 2nd to 9th century AD ~~is attested~~ gradual restoration of the forest and decline ~~of~~ human activity along with a ~~lake deepening~~ ~~due to the advent of more wet climatic~~ conditions. This colder and humid phase corresponded to the Bond 1 Event (1.5 ka BP) cooling episode. Intensive forest clearing around the lake occurred in the 9th – 13th century AD as ~~result of next phase human activity.~~ This period is marked by warming confirmed by a gradual shallowing of the lake (Middle Age Warm Period). Since 14th century AD strong human impact transformed the local landscape, especially ~~by~~ construction and activity mill and ~~creating~~ of a small artificial lake in 15th century AD. This ~~caused that possible climate-induced natural environmental changes are not so clear~~. We can conclude that environmental transformations recorded in bottom lake sediments of Lake Młynek were highly dependent on human activity and were especially intensive in the Roman and Middle Age periods due to favourable climatic conditions. It is important to add here that transformations of Lake Młynek, reconstructed based on diatom analysis, not only indicate changes of the lake water level and correspond with a human impact but also determine episodes of more humid climate during ~~coolings.~~

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ILUSTRATIONS

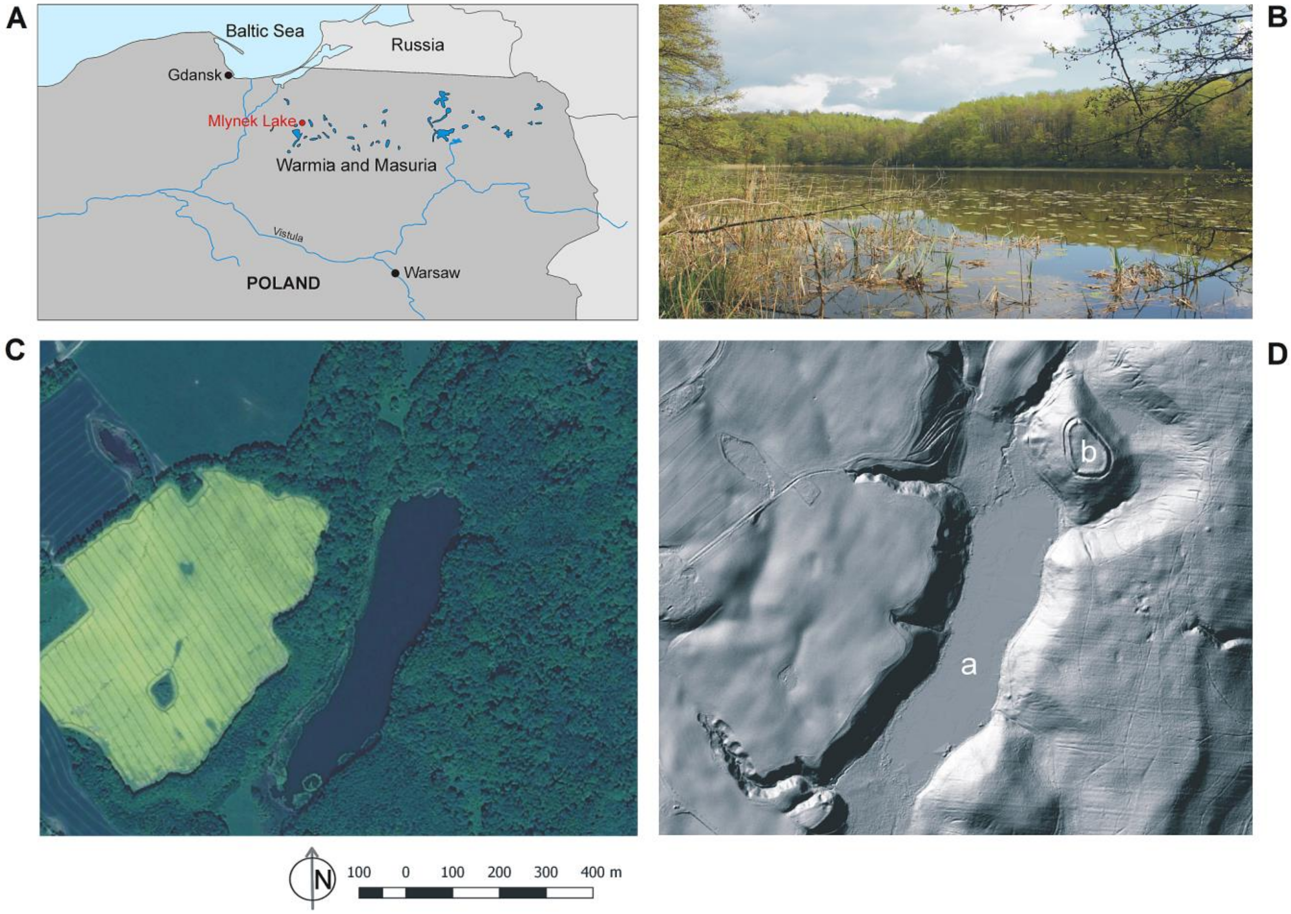

Fig. 1. A - location of Lake Młynek in the Warmia and Mazury Region (north-eastern Poland) (Drawing; Fabian Welc). B – view of the Młynek Lake from the north-west (Photo: Fabian Welc), C – satellite image of the lake (open source: ©Google Earth： www.google.com/intl/pl/earth). D – LIDAR image of the lake: a – lake basin, b – Janiki Wielkie archaeological site established in early Iron Age (open source: ©Geoportal Poland：www.geoportal.gov.pl).

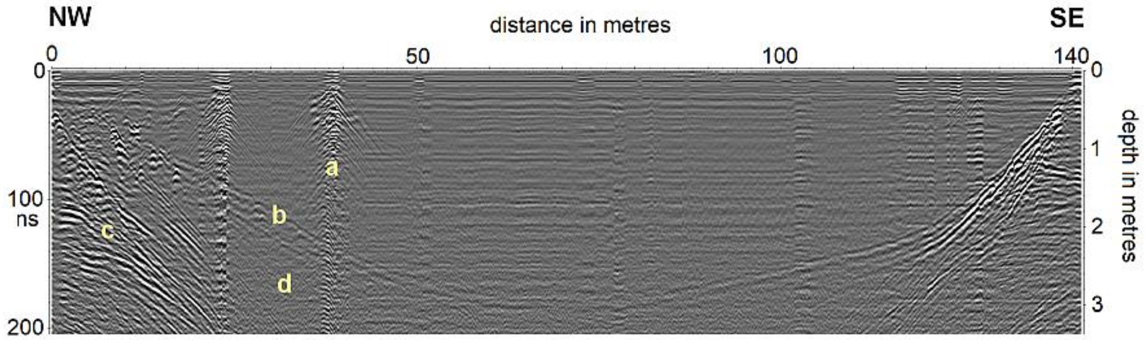

Fig. 2. GPR reflection profile across Lake Młynek (cf. Fig. 2), a – drilling M-1, b – upper boundary of the so-called hard bottom, c –stratified glaciofluvial sandy-gravel beds beneath the lake sediments, d – attenuation zone of electromagnetic waves connected with occurrence of organic sediment (gyttja) (measurements, processing and interpretation: Fabian Welc).

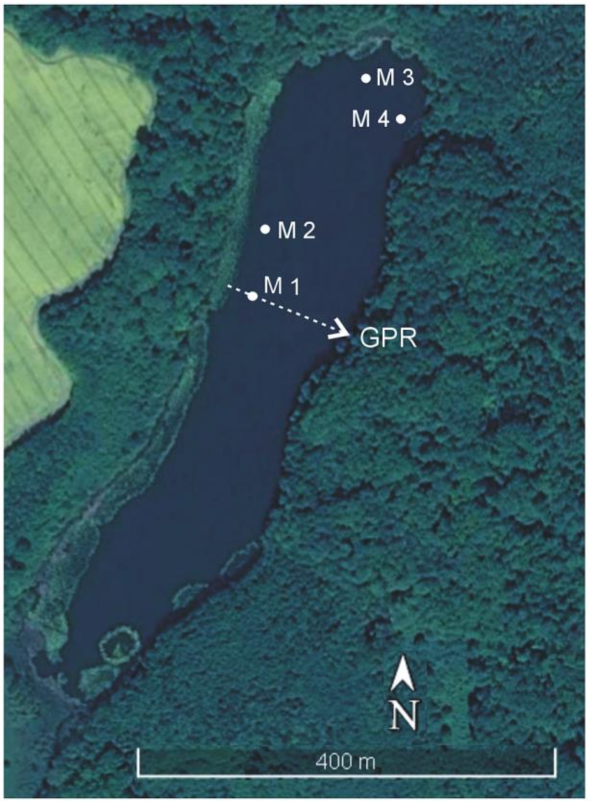

Fig. 3. Młynek Lake: A – location of drillings M 1-4 and transect of GPR sounding (open source: Google Earth©: www.google.com/intl/pl/earth/).

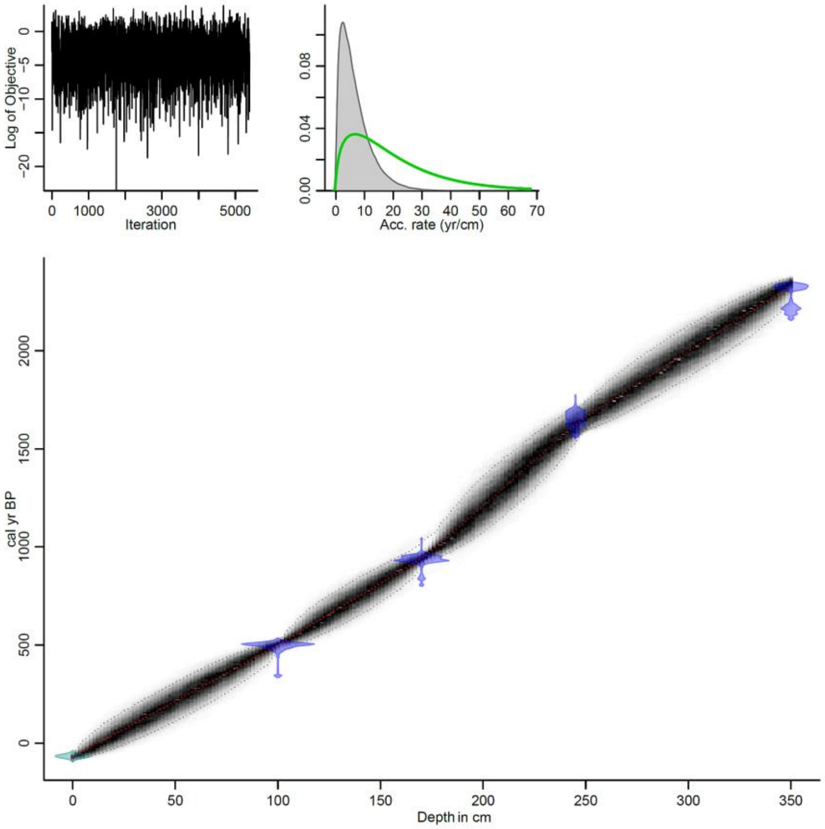

Fig. 4. Age-depth model of the core M-1 from the Lake Młynek sediments. Good runs of a stationary distribution are shown in the upper left panel, green curves and grey histograms in the upper right panel present distributions for the sediment accumulation rate. The main bottom panel shows the calibrated 14C dates (transparent blue) and the age-depth model (darker gray areas) which are indicating calendar ages. Grey stippled lines show 95% confidence intervals and the red curve shows the 'best' model based on the weighted mean age for each depth. The model was created by F. Welc using the open Bacon software (Blaauw and Christen, 2011).

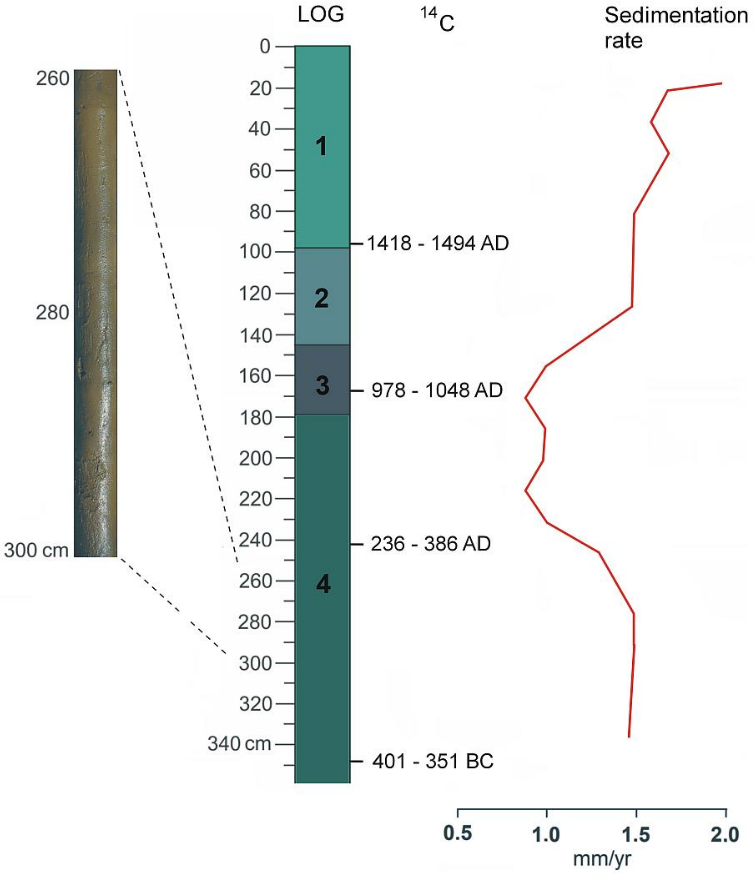

Fig. 5. Lithology of the M-1 borehole with radiocarbon determinations with 95% confidence, close up - photo of the log at 2.6 - 3.0 m depth and sedimentary rate (mm/year) estimated based on the age/depth model. Description of LOG: 1 - hydrated – detritus type gyttja, 2 - very plastic - algal gyttja, 3 - gray-brown peaty - detritus gyttja, 4 - gray-brown gyttja (Photo and drawing: Fabian Welc).

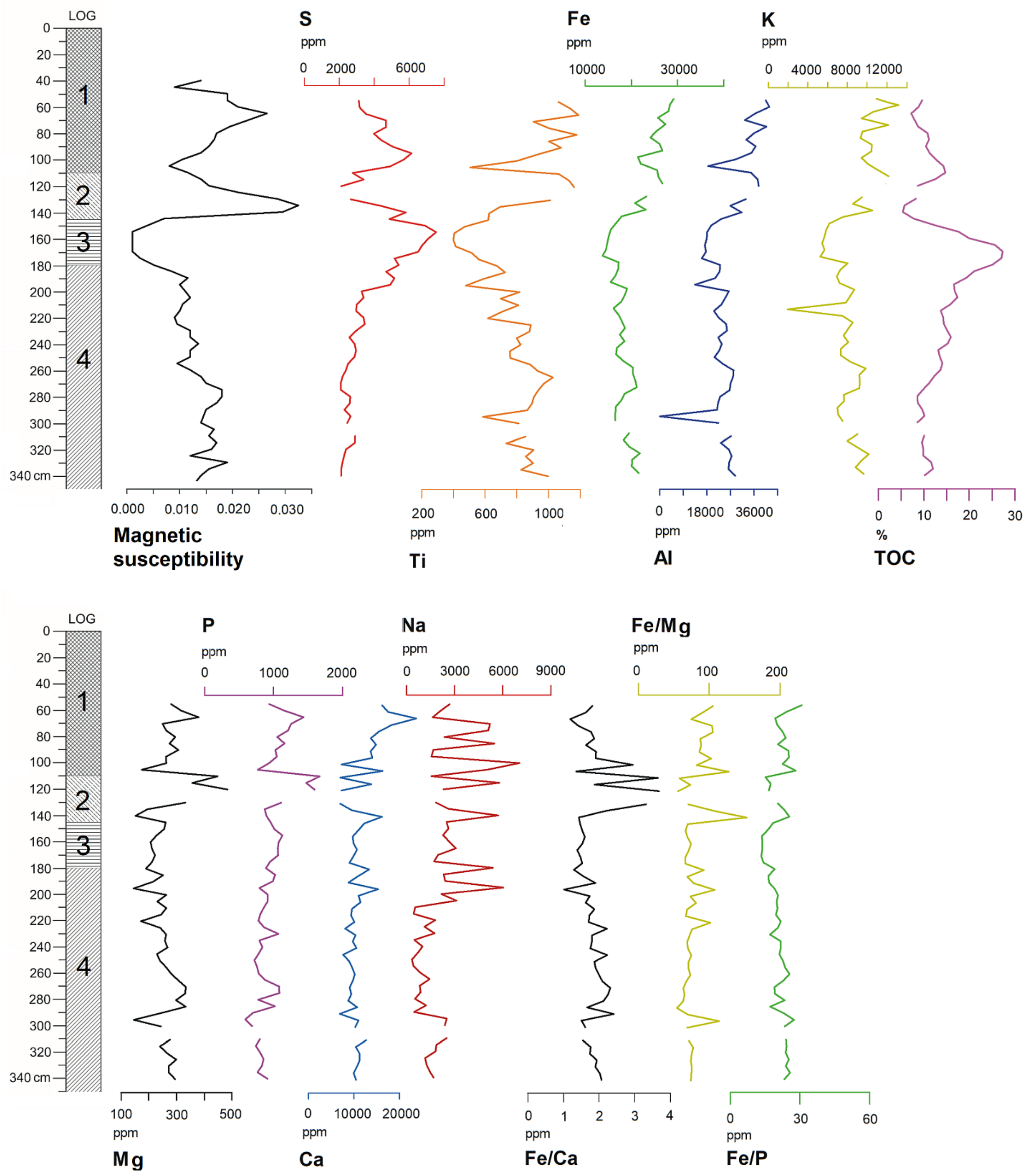

Fig. 6. Concentration depth curves for selected elements and TOC in the core M-1 of Lake Młynek sediments. Description of LOG: 1 - hydrated – detritus type gyttja, 2 - very plastic - algal gyttja, 3 - gray-brown peaty - detritus gyttja, 4 - gray-brown gyttja (Drawing: Fabian Welc).

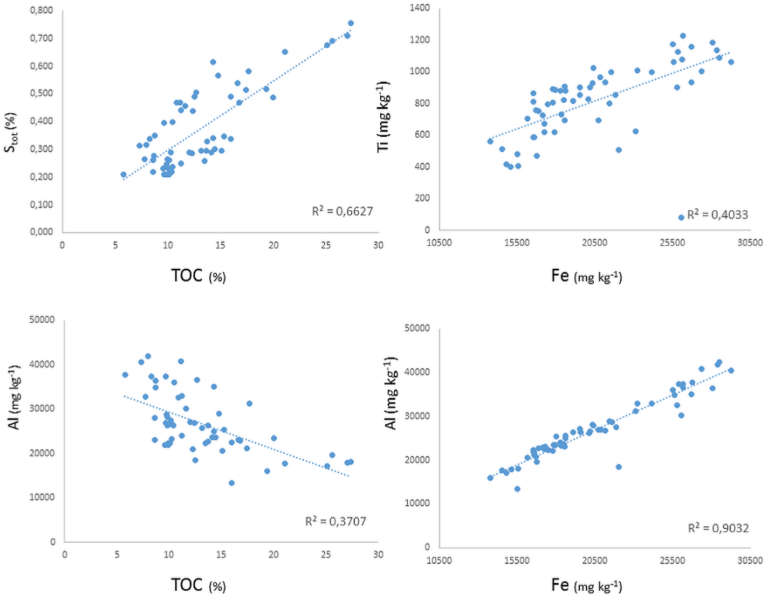

Fig. 7. Scatter plot showing the correlation in the core M-1 between S and TOC, Al and TOC, Ti and Fe, and Ti and Fe. (Drawing: Anna Rogóż-Matyszczak)

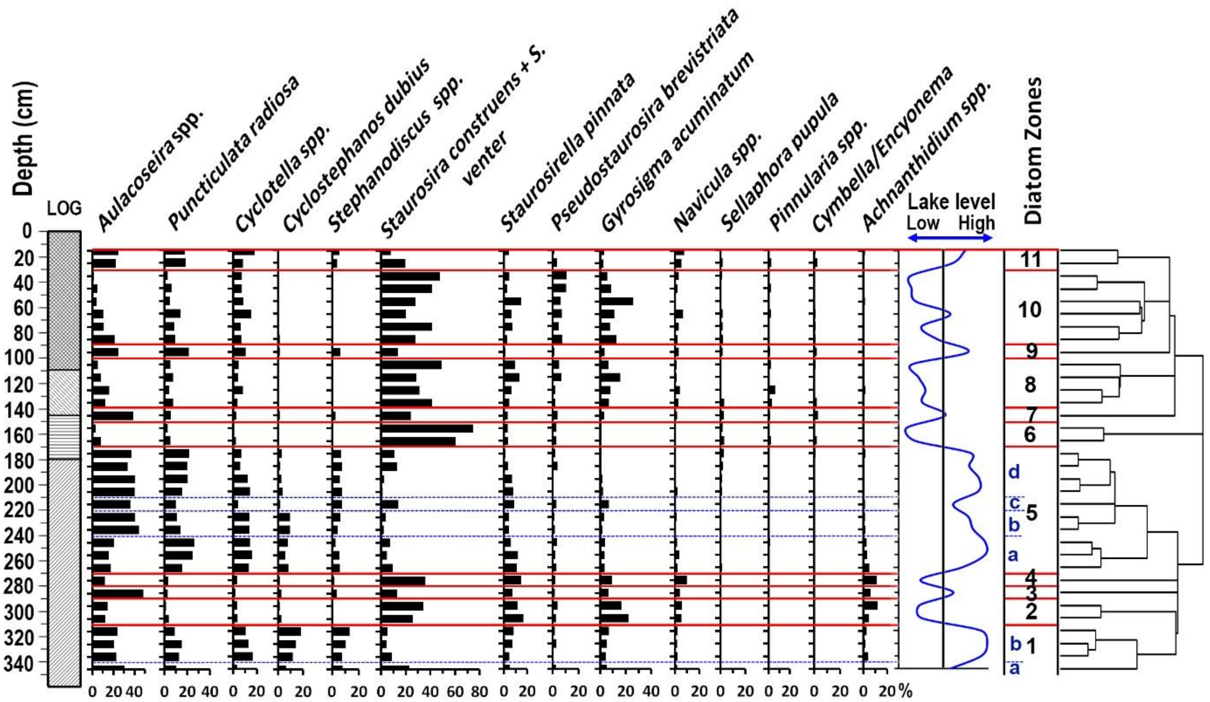

Fig. 8. Diatom stratigraphy of the core M-1, showing diatom zones and lake phases and relative water level changes estimated on relation between planktonic and benthonic diatom taxa (Interpretation and drawing: Abdelfattah Zalat).

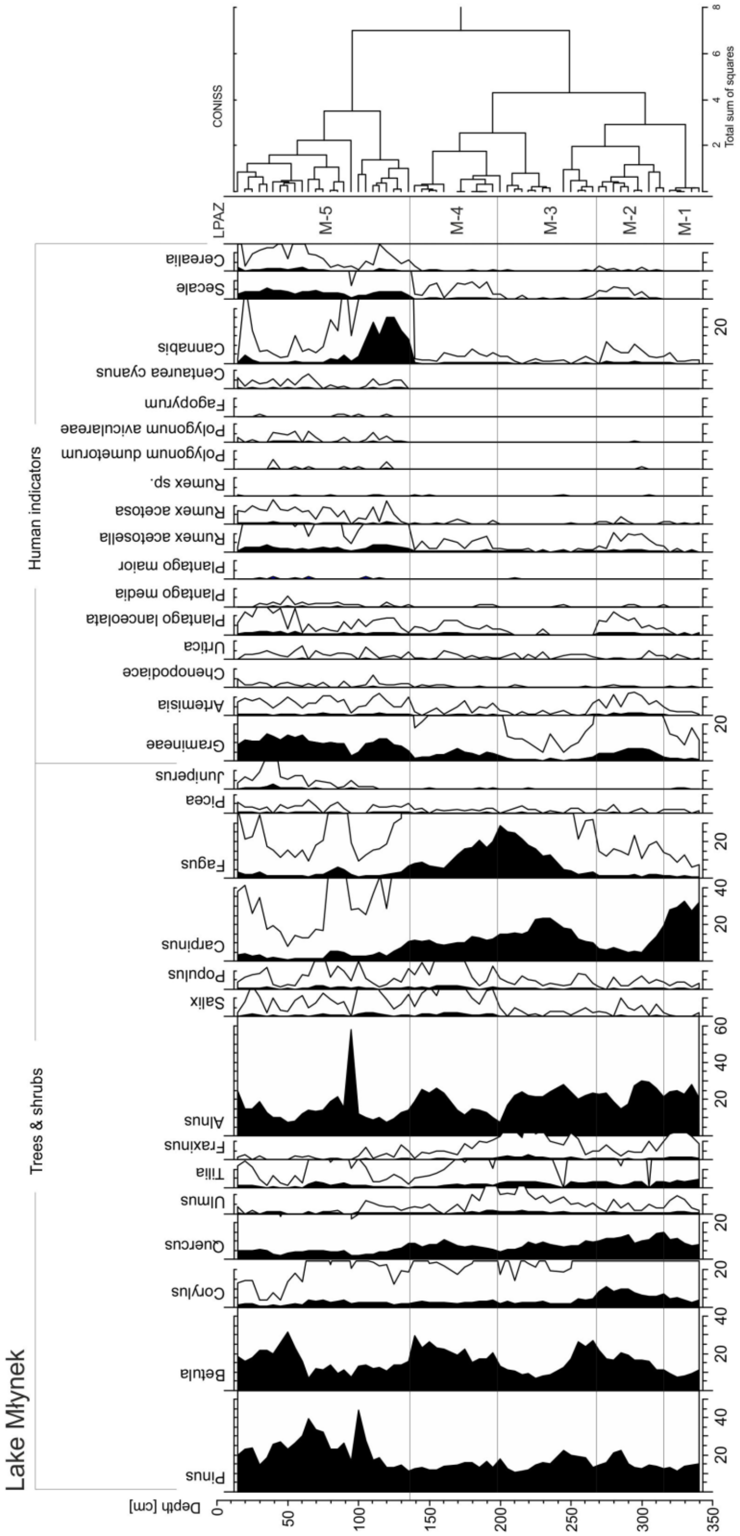

Fig. 9. Percentage pollen diagram from core M-1 – selected taxa.

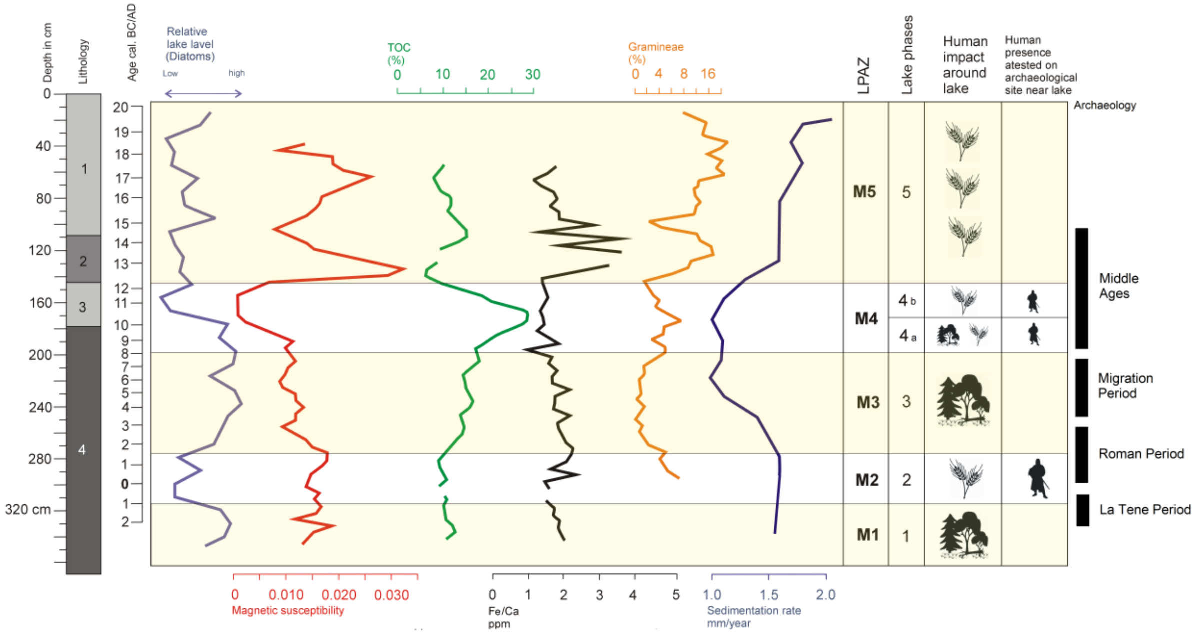

Fig. 10. Diagram with selected palaeoenvironmental proxies including lithology (1 - hydrated – detritus type gyttja, 2 - very plastic - algal gyttja, 3 - gray-brown peaty - detritus gyttja, 4 - gray-brown gyttja) with phases of human activity in the vicinity of Lake Młynek, supplemented by archaeological chronology for Poland (Drawing: Fabian Welc).