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# Last 2400 yrs. Environmental changes and human activity recorded in the gyttja-type bottom sediments of the Młynek Lake (Warmia and Masuria Region, northern Poland)

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## Abstract

In the densely forested Warmia and Masuria region (north-eastern Poland) there are many lakes characterized by small size, calm sedimentation and lack of tributaries, which makes them a very good archive of environmental and palaeoclimatic data for the Holocene. For this reason, one of them - the Młynek Lake, located near the village of Janiki Wielkie, has been selected for multi-faceted palaeoenvironmental research based on a precise radiocarbon scale. Bottom sediments of this reservoir also contain unique information about anthropopression, because a defensive settlement has been operating on its northern shore since the early Iron Age to early Medieval period, which gives opportunity to correlate paleoenvironmental data with phases of the human activity in the last 2400 years. Between 3rd – 2nd century BC the lake was surrounded by a dense forest with domination of warm and wet climate conditions. In turn of 2nd century BC – 2nd century AD forest around reservoir was much reduced, what can be associated with the first - early iron age - occupation phase attested on the stronghold located close to the lake. Between 2nd – 9th century AD gradual restoration of forest and decline of human settlements is attested, along with lake deepening and onset of colder and humid climatic phase which correspond to global cooling episode known as Bond 1 (1.5 ka BP). Period between 9th – 13th century AD indicates again intensive forest clearing around the lake in result of human activity (Middle Age settlement phase on stronghold). This period is characterized by climate change towards warming, which confirms the gradual shallowing of the lake (Middle Age warming period). Since 13 up to 17th century AD intensive cultivation activity around lake tool place. The landscape is subjected to strong human transformations which means that environmental and climate changes are not so clear. However, changes in lake sedimentation can be seen around 1500, which may be associated with so called Little Ice Age - cold interval.

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

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## 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 lake sediment archives is a relatively high and stable sedimentary rate. Well-dated lake sediment columns (by radiocarbon determination for instance) let to trace both long and short term Holocene palaeoclimate (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/spring inflow and outflow (Stankevica et al., 2015). In such water bodies, the sedimentation rate is relatively stable and ongoing continually since initiation of the lakes and may contain not only continuous records of lake history but also of its catchment (Wetzel, 2001; Meyers, 2003; Stankevica et al., 2015). In northeastern Poland as in northeastern Europe, eutrophic lakes are common. They are typical for their substantial primary production (algae and aquatic macrophytes), because of the predominance of nutrient input over mineralization processes (Cooke et al., 2005). Such intensive bio-productivity results in the deposition of thick organic sedimentary sequences, mostly of organic gyttja composed of the remains of aquatic plants, plankton and benthic organisms transformed by activity of 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 size in the Warmia and Mazury Region in north-eastern Poland (Fig. 1). Most of them are located in glacial tunnel valleys formed by meltwater erosion at the termination of the Vistulian (Weichselian) Glaciation (ca. 114-11 ka BP). After deglaciation at the end of the Pleistocene these tunnel valleys were partly filled with deposits and water and persisted in the Holocene. Such lake basins have steep slopes and the lake deposits are underlain by glaciofluvial sand, gravel and silt or by glacial till (Kondracki, 2002; Gałązka, 2009). Many lakes in the Warmia and Mazury Region are small (<1 ha), with stable sedimentation rate and without river inflow and outflow. It is among the reasons that palaeoclimatic investigations, based mainly on pollen analysis are undertaken in this area (e.g., Kupryjanowicz, 2008; Kołaczek et al., 2013).

Młynek Lake, located near the village of Janiki Wielkie, has been selected for multi-faceted palaeoenvironmental research based on a precise radiocarbon scale, as it is hypothesized that the bottom sediments of this lake contain a unique record of human impact, as a result of the location of an Iron Age stronghold on the northern shore, which was active (though not continuously) up

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until the early Middle Ages (Fig. 1). Performed lab analysis defined major lithofacies and the Late Holocene phases of the lake environmental changes were distinguished, based on reconstruction of regional environmental transformations that were in turn steered by the above-regional climate change. Results were correlated with geoarchaeological data to determine mutual relations between environmental and climatic changes with development of human settlements in the Warmia and Mazury Region during the last 2000 years.

## 2. Study area

The Młynek is a small water body that has occupied a glacial tunnel valley since the Holocene. The lake is located in the Iława Lakeland in northern Poland, maintains the NNE-SSW course and it is about 720 m long and 165 m wide. The Młynek Lake occupies 7.5 ha in area, its water surface rises to about 101 m a.s.l. and the maximum depth is just over 2 m. The lake is surrounded by a morainic plateau at 120-130 m a.s.l (Fig. 1).

## 3. Material and Methods

### *3.1. Ground Penetrating Radar*

Determination of lake bathymetry and thickness of bottom sediments are extremely important in paleolimnological research to help locate 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 ice cover of a lake makes sounding much easier and improves access and speed of data collection (Hunter et al., 2003). Measurements along and across the lake were carried out in 2017, directly on a lake ice and a snow cover. We used the radar system ProEx of the Malå Geoscience. 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 4 drillings were done at ca 2 m water depth (Fig. 2) to collect cores according to the Givelet et al. (2004) collecting protocol. Sediment cores were packed into film-wrapped 1 m plastic tubes and transported to the laboratory. These cores (M1-4) were then subjected to magnetic susceptibility measurements results of which enabled to select the core M-1 to detailed analyses as the longest and mostly continuous one. Samples from the 3.5 m long core M-1 (geographic coordinates: 53.82486 N, 19.72419 E) were sub – sampled at 5 cm interval used for multi-proxy laboratory analyses.

*3.3. 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 done in the Poznań Radiocarbon Laboratory in Poland, where $^{14}C$ measurements were performed in graphite targets (Goslar et al., 2004). Construction of proper and correct age-depth model required an assessment of several agents that could disturb constant accumulation of bottom deposits of the Młynek Lake. Disturbances could result both from sedimentary and post-sedimentary processes (varied rate of deposition and compaction, impact of bioturbation). The varied influx of material delivered to the lake from the adjacent area is a very important factor. Therefore, a Bayesian age-depth routine mode was chosen and used, and it takes into account a deposition 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 long length of this core. The Bacon mode uses the IntCal3 curve (Reimer et al., 2013) to calibrate the radiocarbon data.

*3.4. Pollen analysis*

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 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

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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 was 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).

### *3.5. Atomic emission spectrometer (ICP OES)*

ICP-OES spectrometer was used for determination of basic chemical elements in the analyzed samples. 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 was done with the extraction method of elements 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 analyzed in the Spectro Blue ICP OES spectrometer at Regional Research Center 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. Operating parameters were as follows: number of measurements: 3, pump speed: 30 Rpm, coolant flow: 12 l/min, auxiliary flow: 0.90 l/min and nebulizer flow: 0.78 l/min.

### *3.6. Total organic carbon (TOC)*

Analyses were done after sample acidification to remove carbonates in the SHIMADZU SSM 5000A analyzer with a solid sample combustion unit. Method: catalytically aided combustion

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oxidation at 900°C. Pre-acidification, oven temperature: 250°C. Measuring range: TC: 0.1 mg to 30 mg carbon. Sample Amount: 1 gram - aqueous content < 0.5 g. Repeatability: S.D. ±1% of full scale range (www.ssi.shimadzu.com/products/toc-analyzers/ssm-5000a).

*3.7. Magnetic susceptibility (MS)*

The cores from the Młynek Lake 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 magnetic susceptibility. The measurements were done at every 5 cm along each core (M1-4).

*3.8. SEM/EDS*

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. 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, accelerating voltage 5-15keV.

3.10. *Archaeological records*

Archaeological records from the stronghold Janiki Wielkie, built on a hill at the north-eastern shore of the Młynek Lake in the early Iron Age referred to successive human phases detected in the lake sediments, connected with intensified activity of a man near the lake. During archaeological research carried out in 2013 and 2016, a total of 143 stratigraphic units were distinguished, which were divided into seven main settlement phases: phase I-early Iron Age, phase II-leaving the stronghold from the early Iron Age, phase III-early Middle Ages, phase IV-leaving the stronghold in the early Middle Ages, phase V-settlement activity on the stronghold in the 11th-13th century and the last VI phase which is marking finale leaving of the stronghold in the 14th century (Rabiega et al., 2017, Nitychoruk and Welc, 2017)

**4. Results**

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### *4.1. Bathymetry*

A georadar transect across the lake reflects both its bathymetry and lithologic variety of its bottom (Figs. 2 - 3). The superficial layer is composed of an ice layer, 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, there are beneath 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. 3a). The top of the underlying mineral deposits (so-called hard bottom) is indicated as a distinct downward-deflected reflection surface (Fig. 3b). In a 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. 3d), 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 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) in this section 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. 3c).

### *4.2. Age-depth model*

Obtained age-depth model of the core M-1 from the Młynek Lake present calibrated distributions of the individual dates (blue) (Fig. 4). Grey stippled lines show 95% confidence intervals and the red curve shows the 'best' model based on the weighted mean age for each depth. Good runs of a stationary distribution are shown in the upper left panel, green curves and grey histograms in the upper middle panel present distributions for the sediment accumulation rate and memory is indicated in the right panel. The main bottom panel shows the calibrated $^{14}C$ dates (transparent blue) and the age-depth model (darker gray areas) which are indicating calendar ages.

### *4.3. Lithology of the lake sediments*

Deposits in the Młynek Lake are organic-rich. The core M-1 is composed of gray-brown gyttja at depth 1.8-3.6 m (Fig. 5). On depth 1.45-1.80 m dominated gray-brown peaty-detritus

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gyttja. At 1.10-1.45 m was recorded very plastic - [illegible]l gyttja. The uppermost part of the core is composed of gray-brown (depth 0.4 -1.1 m) and hydrated-[illegible]tus type gyttja (0.0-0.4 m).

*4.4. Sedimentary rate*

The sedimentation rate was calculated based on the age-depth model (Fig. 5). Results reflect quite a stable sedimentary environment with a general rate of 1.5 mm a year. There are however parts of the core with a higher or lower rate at 3.46-2.42 m. The rate is stable and equal ca 1.5 mm a year, at 2.42-1.77 mm, drops to 1 mm, then rises at 1.77-0.30 m to 1.3-1.8 mm a year. At 0.0-0.30 m the sedimentary rate is the highest and equal ca 3 mm a year.

*4.5. Magnetic susceptibility and total organic carbon*

The MS of deposits is highly dependent on their lithological composition and grain size content (Dearing, 1994; Sandgren and Snowball, 2001). It reflects not only presence but also 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 their lower values. Total volume of magnetic minerals in lake sediments reflects mostly climatic change in a catchment (Bloemdal and deMenocal, 1989; Snowball, 1993; Peck et al., 1994).

The core M-1 shows MS differentiations but due to organic character of the sediments (Fig. 2), its values are relatively low, from 0.002 to $0.034\times10^{-7}$ units SI. At 3.50-2.58 m, MS rises and drops in turn from 0.01 to $0.02\times10^{-7}$ SI, which partially corresponds to a grey-brown gyttja with organic matter. MS drops at depth 2.60-1.89 m, reaching a minimum at 1.63 m. Higher up, MS rises again reaching the highest value at 1.35 m, then there is a minimum at 1.05 m and the next maximum at 0.69 m.

Magnetic susceptibility 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 Młynek Lake there is an apparent negative relationship between TOC and MS. Several intervals show both higher percentages of TOC and lower MS values. At 1.40 m, TOC indicates a sudden drop, probably due to deforestation and MS is significantly rising due to increasing input of terrestrial (non-organic) material to the lake. Such coincidence clearly indicates that TOC is both autochthonous and allochthonous (Fig. 6)

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Changes in MS in sediments of the Młynek Lake sediments are related most probably to input of clay into the lake and diagenetic conditions in bottom sediments. Iron oxides in the Młynek Lake are most probably of detrital origin and were delivered to the basin through incised deep valleys located at the northwestern shore. Concentration of ferromagnetic minerals is connected with periodical intensified soil erosion around the lake. 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).

### *4.6. Water-soluble ions*

Various factors influence distribution and accumulation of geochemical elements in the 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 Młynek Lake. The curves of S and TOC show significant rises at 2.0-1.4 m that are slightly correlated with decreased contents of Al, Fe, K, Ca, Mg and magnetic susceptibility (Fig. 6).

Sulphur content is correlated with existence of iron sulphides. SEM/EDS analysis indicated occurrence of both phramboidal pyrite and euhedral crystals, characterized as an octahedral crystallized form (Fig. 8). Euhedral crystals are formed as syngenetic in euxinic conditions (Sageman and Lyons, 2003; Berner et al., 2013; Ivanic et al., 2018), whereas phramboidal ones are typical for early diagenetic pyrite but they can still occur as syngenetic ones (Goldhaber, 2003). Phramboids in the examined core are noted at various depths, but they are more common if the TOC content is higher. In the studied core, Fe is positively correlated with Al and Ti (Fig. 8 and table 2). 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). Such occasional high intensity events leave a stronger geochemical imprint, because of sedimentation in shallow water (Ivanić et al., 2018). The highest contents of detrital elements like Al, K, Ca and Mg should 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

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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. 8 and Tab. 2). The association between Al and other elements can be therefore used as a basis for the comparison of natural elemental content in sediments and soils. Most elements like Al, K, Fe and Mg are from terrigenous inputs to the lake. Ca originated mainly from terrigenous bicarbonate inputs and was deposited in the 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 the 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 Mn/Fe ratio is low (0.004 -0.19) in all studied cores and reflects lower $O_2$ concentration in a water column (e.g. López et al., 2006; Naeher et al., 2013), which is typical for eutrophic lakes. The extremely low value (0.004) at depth 3.05 m is probably a response to Fe delivery with terrigenous material. The dysaerobic conditions are also 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) to 43.76 (3.05 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 favors 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

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to anoxic conditions in all studied cores which is typical to eutrophic lakes. Nevertheless, as all proxies are characterized by extreme values at the 3.05 m, 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).

### *4.7. 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. 9). 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 6 diatom assemblage zones (Fig. 9) that reflected 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. The periphytic diatom species dominate the planktonic ones throughout the core. The main change in diatom composition is indicated by a shift from the assemblage dominated by periphytic species through mixed intervals to a planktonic one. 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*. High abundance of eutraphentic planktonic taxa in some interval denotes lake productivity and nutrient concentrations tend to increase with rising water temperature. The marked fluctuations in the abundance of the periphytic to plankton assemblages along the core section explained relative water level changes associated with climate change. 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). Such

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dissolution and deformed diatoms may reflect a dramatic decline in water quality, variations in lake chemistry and shallowness environment. Beside the increase in human activity and anthropogenic nutrient additions to the lake system (Zalat et al., 2018).

### *4.8. Pollen*

Five local pollen assemblage zones (LPAZ M1-M5) were established in the pollen sequence of the Młynek Lake. They reflect regional as well as local vegetation changes, with varied ratios of arboreal (AP) and non-arboreal (NAP) pollen that indicate environmental oscillations (Fig. 10):

| Pollen zones | Depth in meters | Description |
|---|---|---|
| M1 | 3.40-3.20 | Zone represents closed forest communities dominated by hornbeam and alder, which colonized marshland near lake shores. Plants of open spaces are only rarely noted as well as indicators of anthropogenic activity (e.g. *Plantago lanceolata*). There is therefore every reason to conclude that vegetation at that time was relatively natural and not disturbed |
| M2 | 3.15-2.70 | This is the period of major changes in the forest surrounding the lake. Anthropogenic impact on vegetation has led to removal of hornbeam and partial opening of the forest or its fragmentation. The resultant clearings were occupied by birch, pine and hazel. Oak also seems to expand in ecological importance, however its higher frequency is surely caused by increase in pollination under better lighting condition rather than the real expansion of trees. The light gaps were also occupied by a wide variety of herbaceous types. They include apophytes, anthropophytes or cultivated plants - mainly grasses, mugwort Cannabis/Humulus, Plantago lanceolata, Rumex acetosella, Secale and cereals undiff. All this demonstrates the existence in this area of a clear occupation phase. |
| M3 | 2.65-2.05 | This is the level of dynamic restoration of forest communities. The decline of settlements and semi-open habitats generated by them, caused short term expansion of birch into abandoned and open areas, and then replaced by hornbeam rebuilding its position to the level observed in the pollen zone M1. Also elm and ash expand again into riparian forest. All this caused decline of content of birch, pine and hazel. During the second half of the zone we can observe abrupt expansion of beech. Herbaceous plants, abundant in the previous zone are only sporadically noted. |
| M4 | 2.0-1.45 | The lower boundary of the zone marks the onset of another settlement phase and as a result clearing of the forests of similar magnitude as in the M2 pollen zone. First of all disturbances took place in beech forest and to a lesser extent in these dominated by hornbeam. Also in this case open habitats were temporarily occupied by birch (especially toward the end of the zone, when the human activity is lower) and less intensively by poplar. Alder, in the second part of the zone increased in abundance, probably expanded into exposed marginal areas of the lake. The level of anthropogenic activity is only slightly lower to that demonstrated in M2 zone. It is distinguished by the presence of Gramineae, *Artemisia*, *Cannabis*/*Humulus*, *Plantago lanceolata*, *Rumex acetosella*, *Secale* and cereale undiff. |
| M5 | 1.40-0.15 | Pollen zone is characterized by increased intensity of human impact and deforestation. Hornbeam, oak and beech were intensively removed from woodlands. However, in this case the resultant gaps are not occupied by birch. In the two samples, sudden short-term culmination of pine and alder, hard to interpret, are observed. Disturbances in the environment in this level are by far the most substantial. It is clear from the abundant presence of cultivated plant - mainly *Cannabis*, showing clear peak at the beginning. *Secale cereale* and other cereals as well as weeds invading the crops. Also herbaceous plants within open areas - including those on pastures are abundantly noted - Gramineae, *Artemisia*, *Plantago lanceolata*, *P. major*, *P. media*, *Rumex acetosella*, *R. acetosa* and other. |

## 5. Młynek Lake phases of environmental transformation and human activity

Based on results of lithological, geochemical, palynological and diatomological analysis- supplemented by archaeological data, 5 main environmental phases of the Lake Młynek development were distinguished (Fig. 11). Radiocarbon ages supplied with detailed chronology

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whereas pollen data and stratigraphy of the stronghold to the north-east of the lake enabled correlation of human activity with environmental data during the last 2400 years.

*5.a. Phase 1: ca. 2300 – 2100 cal. BP (3.45-3.15 m)*

The lake hydrology was stable and it was quite shallow (Fig. 11). This phase corresponds to LPAZ M-1 which represents closed forest communities dominated by hornbeam and alder. These species colonized marshland near the lake shore. Open community plants and indicators of anthropogenic activity (e.g. *Plantago lanceolata*) are rare, and vegetation around the lake was natural and not disturbed. Diatom assemblage at the beginning of the diatom subzone DZ1 (depth 3.45-3.40 m) indicates a shallow and slightly alkaline lake environment, followed (3.35-3.15 m) by a rising lake level. Common occurrence and domination of *A. granulata* suggests high trophic status of slightly alkaline freshwater environment with high silica concentration (Zalat et al., 2018). MS during this phase is high and it corresponds to high content of Fe, Ti and Al, indicating increased influx of terrigenous material to the lake, presumably activated by more intensive rainfall. High TOC suggest (intensive production of biomass in the lake) relatively wet and warm climatic phase.

*5.1. Phase 2: ca. 2100 – 1830 cal. BP (3.15-2.75 m)*

This is the period of major changes in the environment around the lake, with significant anthropogenic impact. 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 partially open forest whereas oak increase was caused only by higher production of pollen. Mid-forest pastures occupied rather small-scale open areas, as can be seen from higher percentages of *Plantago lanceolata* and other herbaceous plant-e.g. Gramineae, *Artemisia*, *Rumex acetosa*/*acetosella*. Cultivated plants-*Cannabis* t., and *Secale* are rarely noted, however their occurrence is entirely consistent with the other indicator present during this phase. Human occupation is attested by presence of *Cannabis/Humulus*, *Plantago lanceolata*, *Rumex acetosella*, *Secale* and cereals undiff. This period is similarly expressed and commonly noted in numerous palynological sequences in the neighboring area (see for example Noryśkiewicz, 1982, 1987, 2013; Bińka et al., 1991; Ralska-Jasiewiczowa et al., 1998). During this phase, planktonic diatoms were replaced by benthic taxa accompanied by *Gyrosigma acuminatum*, which indicates

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lowering of the lake level and dominance of mesotrophic alkaline freshwater environment. The lower stands were interrupted by short rising water level episode at 2.90–2.85 m (Zalat et al., 2018). Low water level is also confirmed by high frequency peaks of Al, K, Ca, Na, Mg, Fe, V, Cd and S, resulting from delivery of clastic material to the lake, due to reduction of vegetation (cf. Wirth et al., 2013). Presence of pollen taxa as *Plantagolanceolata*, *Rumexacetosella*, *Secale* and cerealia undiff., demonstrates human occupation in the vicinity of the lake. Pollen data indicate that societies of that time cultivated rye and probably hemp. It is the oldest settlement phase at Janiki Wielkie hillfort that corresponds to the end of the La Tène and the early Roman period (1st century BC/1st century AD. Human communities of this time living in the vicinity of the lake can be connected with settlements of the East-Baltic Kurgan Culture (Rabiega et al., 2017).

During phase no. 2 climatic conditions were still similar to these forms previous phase, but more dry - what is reflected by shallowing of the lake. This relatively wet and warm climatic phase should be correlated with so called Roman Climatic Optimum (see., McCormick et al., 2012).

*5.2. Phase 3: 1830 – 1150 cal. BP (2.75-1.95 m)*

This is the level of dynamic recovery of forest communities. Absence of human impact indicators shows decline in populations residing in catchment. Reduction of settlements and semi-open habitats generated by they allowed for short term expansion of birch into abandoned and open areas, and then replaced by hornbeam rebuilding its position to the level observed in the pollen zone M1. Also, elm and ash expand again into riparian forest. All this caused decrease of content of birch, pine and hazel. During the second half of the zone we can observe abrupt expansion of beech. Herbaceous plants, abundant in the previous zone are only sporadically noted. Diatom phase 3 (2.70-2.45 m) present great abundance of planktonic diatoms what indicates deepening of the lake, enhanced thermal stratification, reduced mixing and increased thermal stability (Zalat et al., 2018). Such gradual rise of humidity and cooling resulted in increased vegetation cover and higher lake water level, and it is supported by geochemical indices. There is also a gradual drop in MS, corresponding with decreased content of detrital elements as Fe, Ti, Al and K, accompanied by a rise of TOC and of the ratio Fe/Ca. Lower MS and content of Al (acting as a major constituent of soils) with higher TOC suggests extension of vegetation cover, resulting in limited erosion in spite of gradually higher precipitation in the lake catchment and therefore, rise of its water level. In this phase there are no traces of human activity ~~at the settlement~~ nearby (Rabiega et al., 2017).

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The climate in phase 3 is gradually changing towards cooler, but also more humid. There is an increase in rainfall and a decrease in evaporation, which is reflected in lake sedimentation, where the lake deepens, resulting in a reduction in the sediment installment showing less productivity and greater lake stability. This phase should be associated with the global cooling episode known as Bond 1 (1.5 ka BP) (see., Bond et al., 1997; Welc, 2019)

*5.3 Phase 4: 1150 – 780 cal. BP (1.95-1.45 m)*

Phase no. 4 is correlated with palynological zone M4 and was divided into two subphases 4a and 4b (Fig. 11). The lower boundary (subphase 4a) of this zone marks the onset of another settlement phase and as a result clearing of the forests of similar magnitude as in the M2 pollen zone. First of all, disturbances took place in beech forest and to a lesser extent in these dominated by hornbeam. Also, in this zone, birch and less intensively poplar occupied temporarily abandoned open areas (especially toward the end of the zone, when the human activity is lower). Alder, in the second part of the zone increased in abundance, probably expanding into exposed marginal areas of the lake. The level of anthropogenic activity is only slightly lower to that demonstrated in M2 zone and reflected by the presence of Gramineae, *Artemisia*, *Cannabis*/*Humulus*, *Plantago lanceolata*, *Rumex acetosella*, *Secale* and cerealia undiff. Diatom assemblages indicate a deepening of the lake (Zalat et al., 2018). In this time synanthropic plants disappear and they come back again in the early Middle Ages about 700 AD. Higher TOC corresponds with lower content of detrital material (Fe, Ti, Al and K) and lower MS, and it can be interpreted as progressing humidity (Fig. 6). This phase can be correlated with the Migration Period and the early Middle Ages. At the end of the phase 4 during the early Middle Ages, in the settlement close to the lake (archaeological phase III) after removal of the layers formed by natural development of a soil (due to abandonment of the site in the early Roman Period) a defence rampart was raised. At its upper surface a wooden-loamy wall was constructed. After short period this stronghold was destroyed. A charcoal from a fired wall represents this destruction phase at the end of the 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).

Subphase 4b (1.70-1.45 m) marks the onset of another settlement phase, resulting in further forest clearing around the lake and increase in birch invading into open areas. In this period alder which expanded into exposed marginal areas increased in abundance. This is documented by the

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great abundance of *Aulacoseira* species associated with *Puncticulata radiosa* in the upper part of diatom zone 5 at 1.85-1.70 m. The diatom assemblage suggests episode of relative rising lake level, increased trophic state of the lake and stronger turbulent mixing conditions. Moreover, the greatest reduction of abundance *Fragilaria sensu lato* accompanied by a high abundance of *A. granulata* could have resulted from forest clearings around the lake caused by settlers. In this time alder increased its abundance as it probably expanded into exposed marginal areas of the lake. The anthropogenic activity, expressed by presence of herbaceous plants (including cereals) Gramineae, *Artemisia*, *Cannabis* t., *Plantago lanceolata*, *Secale* and cerealia undiff. as well as by forest clearings is only slightly lower than in the zone M2 and generally it resembles those in the Roman Period. Towards the end of this phase some decline in intensity of human impact is observed.

Subphase 4b corresponding to diatom zone 6 which is characterized by high abundant benthic *Fragilaria sensu lato* species with sporadic occurrence of planktonic taxa. The diatom assemblage reflects lowering water level and slight alkaline freshwater, lower nutrient concentrations, low silica content (Zalat et al., 2018). In the strongholds at the lake shore, the next human activity phase 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 area of 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 mowing towards the yard and the moat (Rabiega et al., 2017). After the early Middle Ages, the area around the lake was occupied by the Prussian tribe of Pomezanians and this region named Geria was a borderland. It consisted of network of strongholds located among others at Bądki, Urowo, Wieprz and Kraga (Szczepański, 2009). In the south the tribe bordered directly with the Slavic settlement, which includes two strongholds located around 30 km away from Janiki at Łanioch near the Silm Lake in the SSE and Zajączki near Ostróda in the SE (Grążawski, 2006).

Phase 4 is marked by continuation of previous climatic conditions, which are gradually influenced by human activity. Subphase 4b is characterized by climate change towards warming, which confirms the gradual shallowing of the lake and increasing the rate of sedimentation. Under this sub-phase, human impact on the environment is already so great that the picture of 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 (see, Mann et al., 2009).

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### *5.4.Phase 5: 780 cal. BP (1.45- 0 m)*

This phase starts about 1200 AD and is connected with the Middle Ages early Modern Period. Intensive cultivation and treatment of hemp is terminated but cultivation of cereals and presence of synanthropic plants indicates human activity in a direct vicinity of the lake. The water level is not high and slightly changes. At 1.4 m there is a drop in TOC, probably due to deforestation. MS is significantly rising at the same depth as result of increasing input of terrestrial material to the lake, presumably caused by human activity (deforestation). The intervals of increased precipitation were reflected by significantly more intensive terrestrial runoff to the lake. This statement is confirmed by quasi-linear correlation of MS with contents of Fe and Ti in sediments (Fig. 8). The modern evolution of the lake resulted in development of a shallow (2-3 m) and gradually overgrowing lake.

Phase 5 is a period of increased human activity around the lake, which means that environmental and climate changes are not so clear. However, changes in lake sedimentation can be seen around 1500, which may be associated with the development of the Little Ice Age (see., Büntgen, U., Hellmann, 2014).

## 5. Conclusions ~~and discussion~~

The presented scenario of environmental changes in the Młynek Lake and its vicinity during the last ca. 2400 years can be recapitulated in the following way. In the phase 1 (3$^{rd}$-2nd century BC) the lake was surrounded by a dense forest and it was not deep. Increased influx of terrigenous material to the lake can be connected with periods of more intensive local precipitation. A climate was quite warm and wet. The phase 2 (2nd century BC-2nd century AD) is a period of major changes in the environment around the lake, with increasing anthropogenic impact. The forest was much reduced. Intensive human activity is attested by presence of *Cannabis/Humulus, Rumex acetosella, Secale* and cereals undiff. Diatoms indicate a drop of the lake water level. The oldest settlement phase was identified in the stronghold close to the lake (end of the La Téne and the Roman periods). This relatively wet and warm climatic phase should be correlated with so called Roman Climatic Optimum. The phase 3 (2$^{nd}$-9th century AD) indicates gradual restoration of forest communities and absence of synanthropic plants what proves a decline of human settlements around the lake. The middle part of this phase should be associated with the global cooling episode known as Bond 1 (1.5 ka BP). The next - phase 4 (5$^{th}$-13th century AD) is expressed by forest clearing restoration around the lake and onset of the next settlement phase. At the end of this phase a defence rampart was raised in the stronghold and a wooden-loamy wall was constructed on it. The lower boundary of phase ($10^{th}$-13th century AD) indicates further intensive forest clearing around the lake. Human activity is marked by presence of Gramineae, *Artemisia*, *Cannabis*/*Humulus*, *Plantago lanceolata*, *Secale* and *Cereale* undiff. It corresponds with a beginning of the next settlement phase in the stronghold (end of 11th century AD) when the next rampart was raised, with wooden constructions at its top. The stronghold was finally abandoned in the first half of the 13th century AD. This period is characterized by climate change towards warming, which confirms the gradual shallowing of the lake (Middle Age warming period). The phase 5 (since 13th century AD up to present) is reflected by intensive cultivation and treatment of hemp and cereals close to the lake during intensive colonisation of Warmia and Masuria by Teutonic state. The water level is not high and changes slightly only, presumably due to reclamation works. The landscape is subjected to strong transformations connected with anthropopression, resulting in significant deforestation of the area. The landscape is subjected to strong human transformations which means that environmental and climate changes are not so clear. However, changes in lake sedimentation can be seen around 1500, which may be associated with so called Little Ice Age - clod interval.

The above scenario seems to be confirmed by earlier paleoenvironmental research conducted in the southwestern part of the Warmia-Masuria Lake District (Kupryjanowicz, 2008; Kołaczek et al., 2013). Earlier studies of lake sediments in the Warmia and Mazury Region were based mainly on palynological examination, a comparyson of the Młynek Lake sequence with other sites must also be based on palynology (Fig. 12). As it was mentioned, the Lake Młynek located in the wide zone of Lakelands of north-eastern Poland. The closest site Woryty (Pawlikowski et al,.1982, Noryśkiewicz and Ralska-Jasiewiczowa 1989, Ralska-Jasiewiczowa and Latałowa, 1996), ca. 35 km in a straight line to the east is a reference for this area. The paleoenvironmental records delivered by the Młynek Lake core is very similar to the Woryty palynological succession with the human impact during the Roman period and the Medieval time. More detailed comparison is impossible, because of low resolution of the pollen spectrum at Woryty. The Lake Drużno, ca. 35 km to the north (Zachowicz et al. 1982, Zachowicz and Kępińska 1987, Miotk-Szpiganowicz et al. 2008), is the second closest site with palynological examination to the Młynek Lake. Low resolution and lack of age-depth model from this lake makes comparison of pollen results between these two sections difficult. Even though the Drużno Lake is located in the Vistula Delta depression, the pollen record for the last 2400 years is similar to the Młynek Lake one with human impact marked out during the Medieval time and presence of human indicators during the Roman period. Differences in natural vegetation are local and especially exposed in higher share of alder in pollen diagram from the Drużno Lake, most probably caused by wet habitats in the Vistula Delta. In the 2013 year were published New palynological data from the Łańskie Lake (Madeja, 2013), located ca. 55 km to the south-east from the Młynek Lake show higher percentages of pine and lower share of beech. This record results probably not only from different environmental conditions in the lake vicinity but also different size of the lakes. The Młynek Lake is a very small (ca. 0.7 $km^2$ ) and mid-forest basin, whereas the Łańskie Lake area is over 10 $km^2$ and shows much more regional pollen record. Based on periodical appearances of plant human indicators and archaeological data between 300 BC and 800 AD Madeja (2013) distinguished three human phases of West Baltic Barrow, Wielbark and Prussian cultures. In the palynological diagram from the Młynek Lake (Phase 2) the first is indicated only, including termination of the La Tene and the Roman Period. Significant growth of human indicators from 1000 yrs. AD is visible in diagrams from both sites. A more local record from the Młynek Lake is marked especially by high percentage of *Humulus*/*Cannabis* pollen grains (up to 25%), in 13-15th centuries. In the sediments of the Łańskie Lake, presence of pollen grains of hemp was discontinuous and not exceeded 1%.

Numerous pollen data are available from the area adjacent to the south-west. The investigation from the Brodnica Lake District i.e. Strażym Lake (Noryśkiewicz, 1987, Noryśkiewicz and Ralska-Jasiewiczowa 1989), Oleczno Lake (Filbrandt-Czaja, 1999, Filbrandt-Czaja et al. 2003) and Chełmno Lakeland (Noryśkiewicz 2013) presents human activity in the Neolithic. Palynological record from this region evidenced settlement during La Tene, Roman and Medieval periods. Comparison of the pollen record from other sites located to the east of the Młynek Lake shows differences in share of a beech. The content of *Fagus silvatica* pollen grains changes in the north-eastern direction and significantly high content of *Fagus silvatica* in the Młynek Lake sediments is caused by a very local record from a small lake. Decline of *Fagus sylvatica* is related to continental climate and is visible in a pollen diagram from Salęt Lake (Szal et al. 2014a), Mikołajki Lake (Ralska-Jasiewiczowa 1989), Żabińskie Lake (Wacnik et al. 2016) and Wigry Lake (Kupryjanowicz 2007). Simultaneously with beech decline, a share of *Picea abies* increases. A record of human activity in palynological spectra from eastern Poland was noted in many sites. There is similarity between pollen records from the Młynek Lake and far away over 100 km to the east in the Masurian Lakes: Wojnowo, Miłkowskie and Jędzelek (Wacnik et al. 2014). Recorded shorter or longer human impact on vegetation during Roman Period and Medieval time is divided by ca. 500-600 years without cultivation and with natural reforestation (and strong share of birch, a pioneer tree). Similar duration of human regression in the Lake Młynek profile began and terminated earlier than recorded in the lakes Wojnowo or Miłkowskie. Different history of human activity shows the results from the Lake Salęt (Szal et al. 2014b). Pollen grains of cultivated and ruderal plants are present continuously from the early Iron Age to the early Medieval time. In opposite to the Młynek Lake or Wojnowo and Miłkowskie pollen record, the suggested constant settlement in the neighborhood of the Salęt Lake occurred with a very short decline of human impact only in 880-980 AD (Szal et al. 2014a). Cited examples of palynological reconstruction of vegetation changes under climatic conditions and human impact reflect differences between a record from the Młynek Lake and much larger and predisposed regional view of environmental history.

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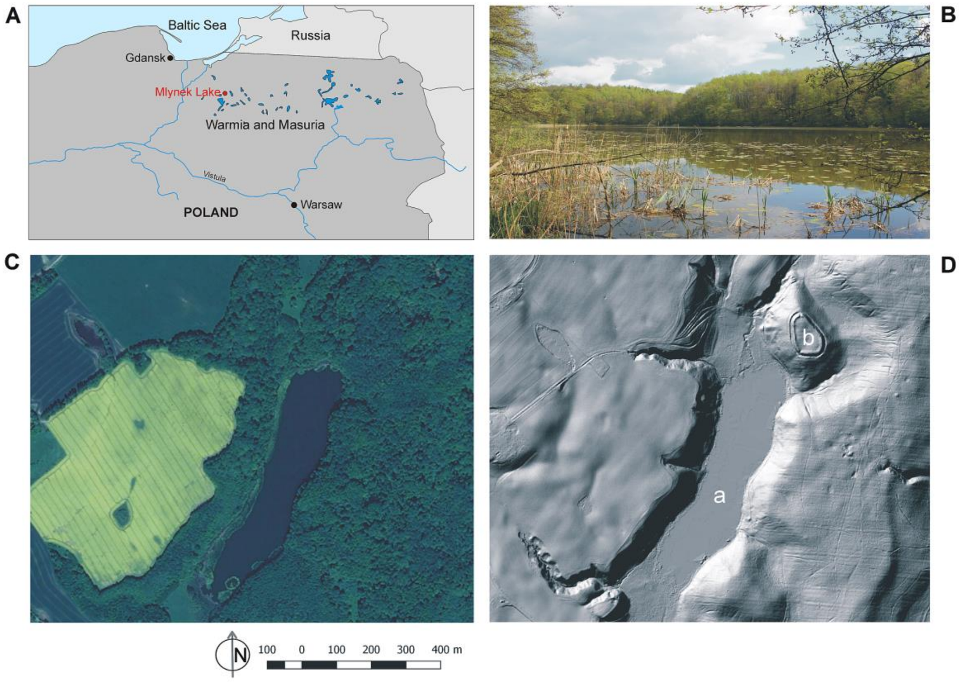


Fig. 1. A-location of the Młynek Lake in the Warmia and Mazury Region (north-eastern Poland) (Drawing; Fabian Welc). B-view of the Młynek Lake from the north-west (Photo: Fabian Welc), C-satellite image of the lake (open source: ©Google Earth： www.google.com/intl/pl/earth). D-LIDAR image of the lake: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

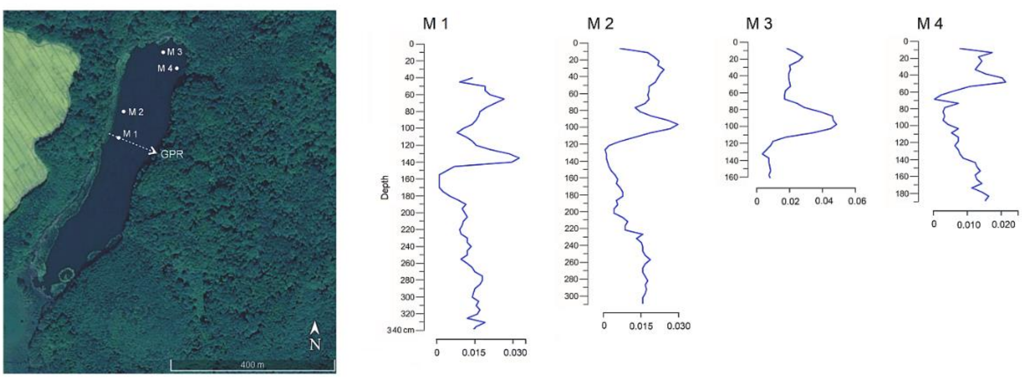


Fig. 2. Młynek Lake: A-location of drillings M 1-4 and transect of GPR sounding (open source: Google Earth©: www.google.com/intl/pl/earth/). B-results of magnetic susceptibility measurements of the cores M 1-4 (Drawing: Fabian Welc).

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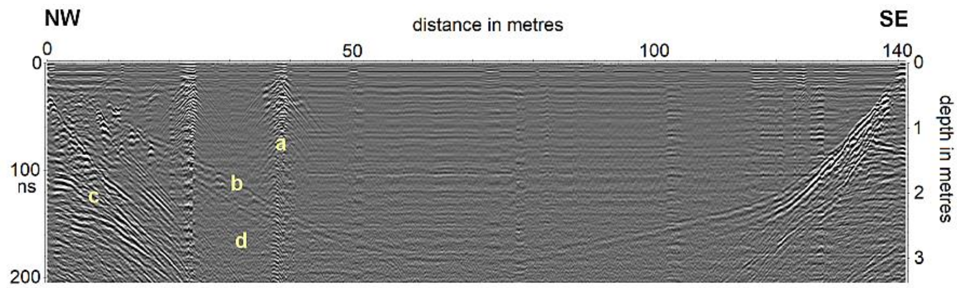


Fig. 3. GPR reflection profile across the Młynek Lake (cf. Fig. 2), a-drilling M-1, b-upper boundary of the so-called hard bo[illegible] c-stratified glaciofluvial sandy-gravel beds beneath the lake sediments, d-attenuation zone of electromagnetic waves connected with occurrence of organic sediment (gyttja) (measurements, processing and interpretation: Fabian Welc).

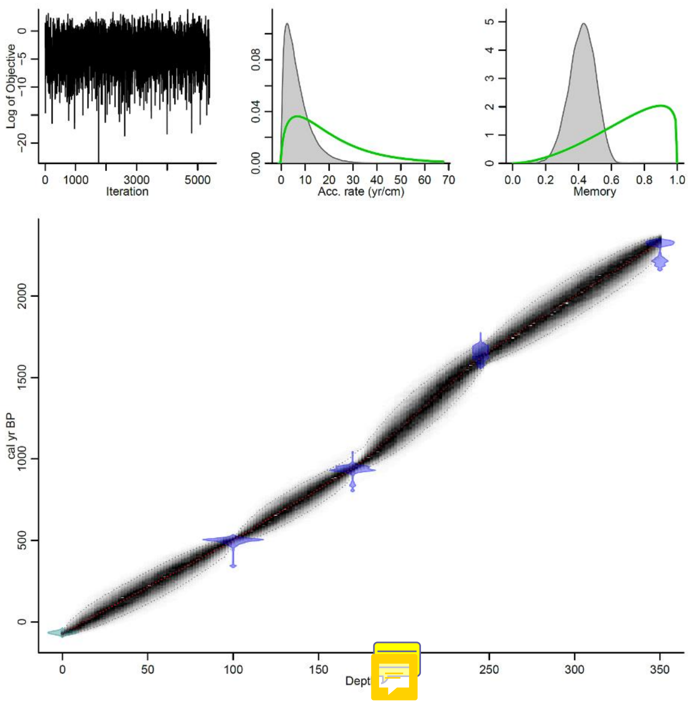


Fig. 4. Age-depth model of the core M-1 from the Młynek Lake. Good runs of a stationary distribution are shown in the upper left panel, green curves and grey histograms in the upper middle panel present distributions for the sediment accumulation rate and memory is indicated in the right panel. The main bottom panel shows the calibrated $^{14}$C 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).

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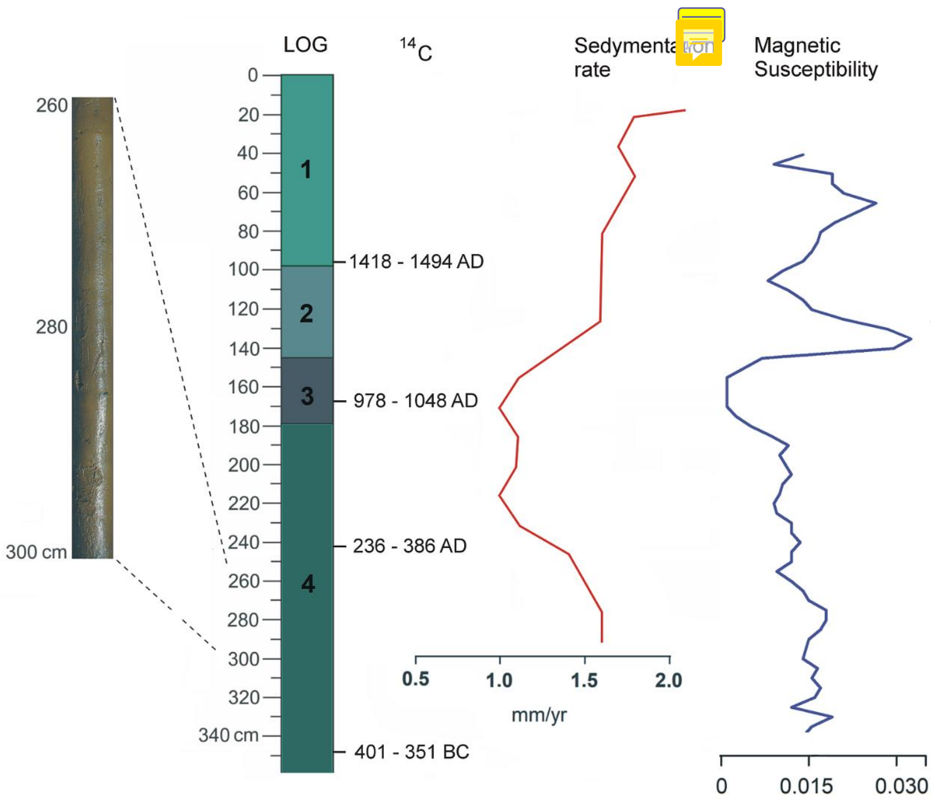


Fig. 5. Lithology of the M-1 borehole with radiocarbon determinations with 95% confidence, close up-photo of the log at 2.6-3.0 m depth and sedimentary rate (mm/year) estimated based on the age/depth model and magnetic susceptibility. Description of LOG: 1-hydrated and detritus type gyttja, 2-very plastic-algal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

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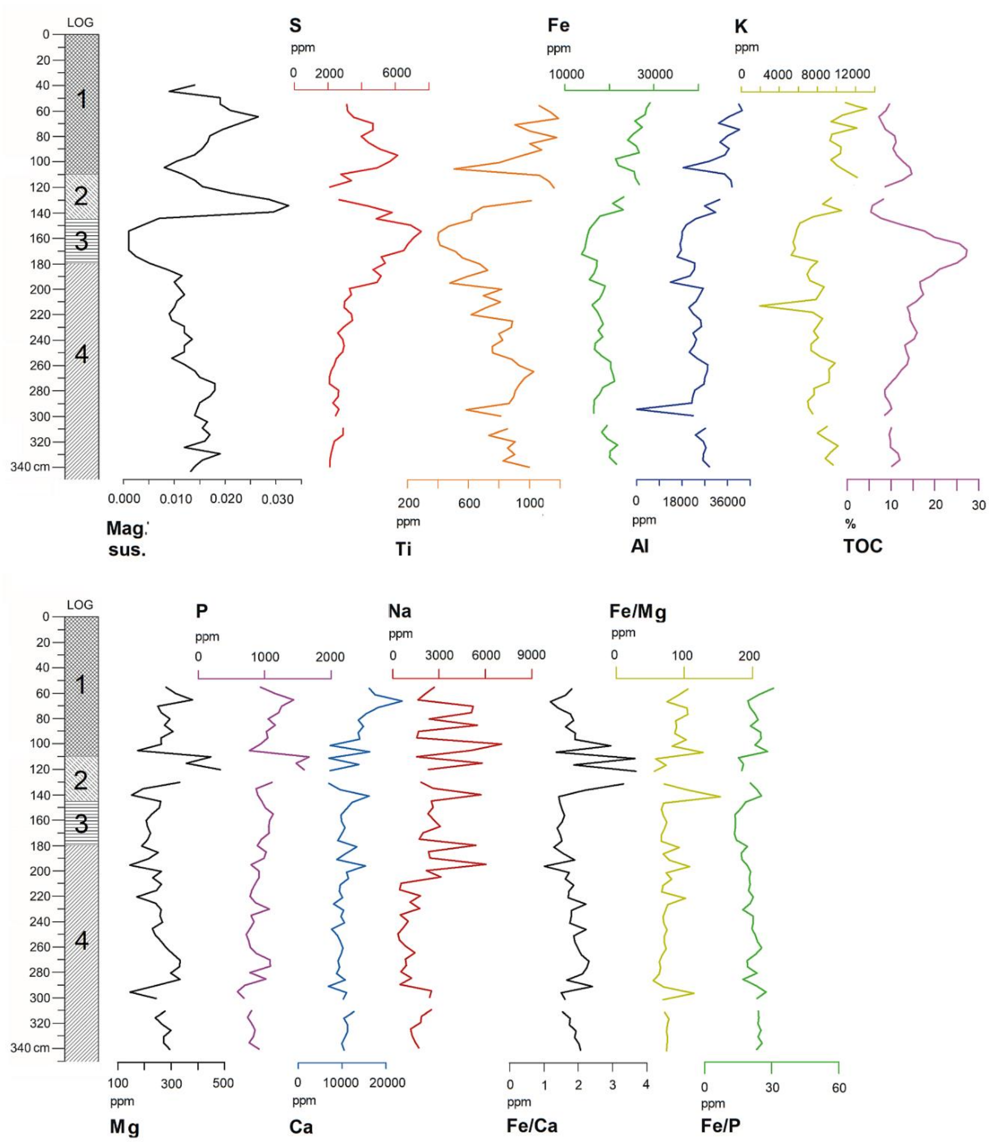


Fig. 6. Concentration depth curves for selected elements and TOC in the core M-1 of the Młynek Lake sediments. Description of LOG: 1-hydrated-detritus type gyttja, 2-very plastic - algal gyttja, 3-gray-brown peaty-detritus gyttja, 4-gray-brown gyttja (Drawing: Fabian Welc).

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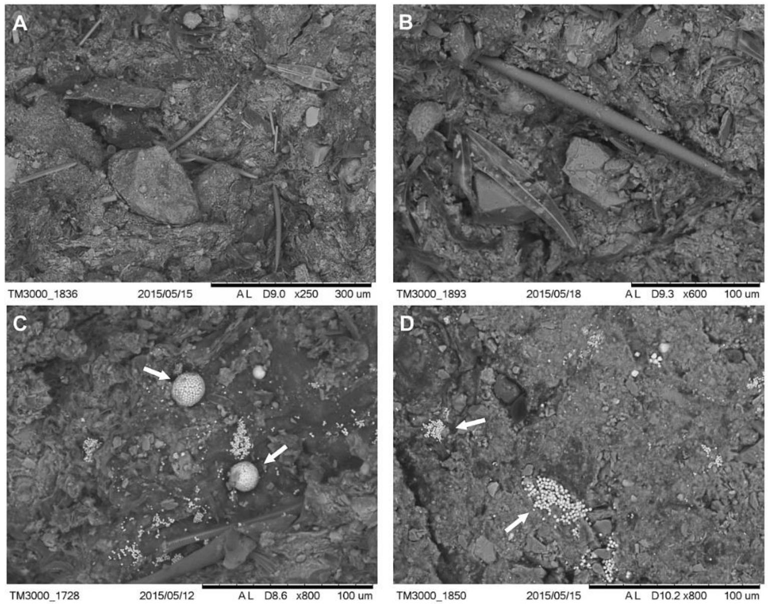


Fig. 7. Core M-1 SEM images showing a general view of the Młynek Lake sediments. Pictures A and B present mostly freshwater diatoms sponge spicules and plant detritus. Pictures C and D show the characteristic pyrite aggregates, marked by arrows (Photos: Anna Rogóż-Matyszczak)

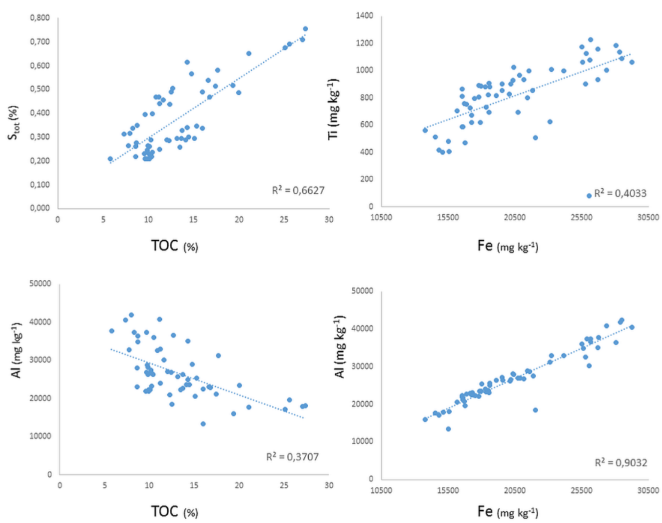


Fig. 8. Scatter plot showing the correlation in the core M-1 between S and TOC, Al and TOC, Ti and Fe, and Ti and Fe. (Drawing: Anna Rogóż-Matyszczak)

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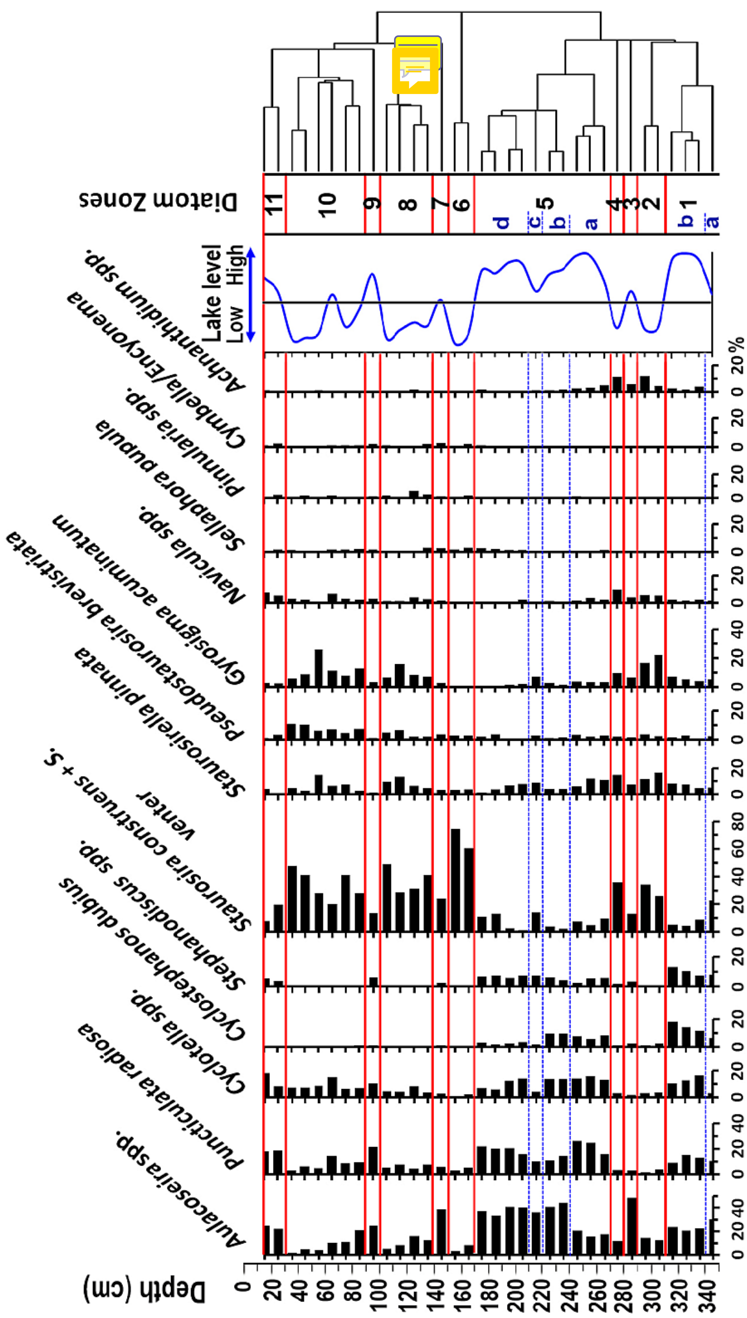


Fig. 9. Diatom stratigraphy of the core M-1, showing diatom zones and lake phases and relative water level changes estimated on relation between planktonic and benthonic diatom taxa (Interpretation and drawing: Abdelfattah Zalat).

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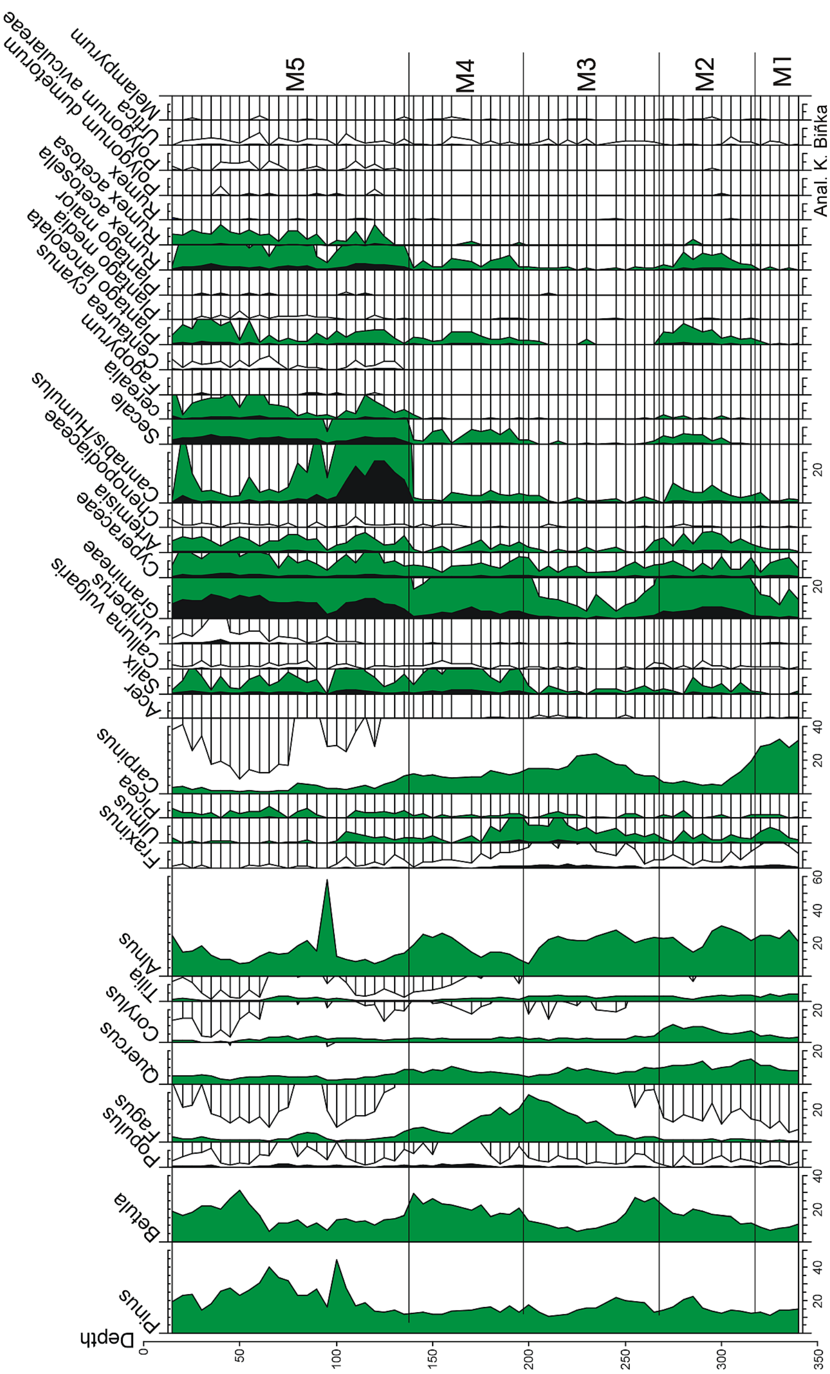


916 Fig. 10. Simplified pollen diagram of the core M-1 (Interpretation and drawing: by Krzysztof Bińka).

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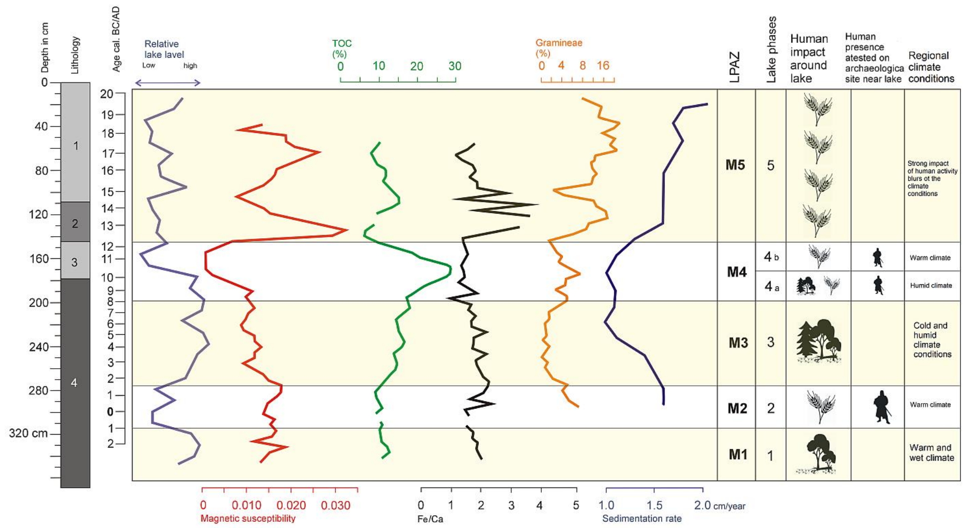


Fig. 11. Diagram with selected palaeoenvironmental proxies including lithology (1-hydrated – detritus type gyttja, 2-very plastic - algal gyttja, 3-gray-brown peaty-detritus gyttja, 4-gray-brown gyttja) with phases of human activity and local climate conditions dominated in the vicinity of the Młynek Lake 9 (Drawing: Fabian Welc).


Fig. 12. Map of north-eastern Poland (Warmia and Masuria region) with location of the most important lakes mentioned in text: 1-Młynek Lake, 2-Woryty Lake, 3-Drużno Lake, 4-Łańskie Lake, 5-Strażym Lake, 6-Salent Lake, 7-Mikołajki Lake (Drawing: Fabian Welc).

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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 |

Table 2. Pearson correlation coefficient (PCC) for selected elements (upper table - A) and proxies (lower table - B).

A

| | Al | As | Ca | Ce | Cr | Cu | Er | Fe | Ga | La | Li | Mn | Nd | Ni | P | Pb | Pr | Rb | Sc | Sr | U | V | Ti | S | TOC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Al** | 1.00 | | | | | | | | | | | | | | | | | | | | | | | | |
| **As** | 0.37 | 1.00 | | | | | | | | | | | | | | | | | | | | | | | |
| **Ca** | 0.36 | 0.12 | 1.00 | | | | | | | | | | | | | | | | | | | | | | |
| **Ce** | 0.00 | 0.61 | -0.29 | 1.00 | | | | | | | | | | | | | | | | | | | | | |
| **Cr** | 0.17 | -0.05 | 0.67 | -0.08 | 1.00 | | | | | | | | | | | | | | | | | | | | |
| **Cu** | 0.63 | 0.24 | 0.32 | -0.20 | 0.05 | 1.00 | | | | | | | | | | | | | | | | | | | |
| **Er** | 0.39 | -0.03 | -0.17 | 0.26 | -0.07 | -0.15 | 1.00 | | | | | | | | | | | | | | | | | | |
| **Fe** | 0.95 | 0.39 | 0.52 | -0.05 | 0.29 | 0.59 | 0.34 | 1.00 | | | | | | | | | | | | | | | | | |
| **Ga** | 0.08 | -0.36 | 0.71 | -0.54 | 0.73 | 0.04 | 0.01 | 0.23 | 1.00 | | | | | | | | | | | | | | | | |
| **La** | 0.15 | 0.67 | 0.13 | 0.44 | -0.01 | 0.01 | -0.02 | 0.22 | -0.21 | 1.00 | | | | | | | | | | | | | | | |
| **Li** | 0.33 | 0.35 | 0.19 | 0.01 | -0.01 | 0.50 | -0.07 | 0.29 | -0.04 | 0.05 | 1.00 | | | | | | | | | | | | | | |
| **Mn** | 0.46 | 0.38 | -0.35 | 0.45 | -0.38 | 0.07 | 0.50 | 0.38 | -0.61 | 0.30 | 0.10 | 1.00 | | | | | | | | | | | | | |
| **Nd** | 0.06 | 0.58 | -0.24 | 0.95 | -0.05 | -0.22 | 0.31 | 0.02 | -0.53 | 0.43 | -0.03 | 0.52 | 1.00 | | | | | | | | | | | | |
| **Ni** | 0.15 | -0.01 | 0.62 | -0.01 | 0.99 | 0.03 | -0.05 | 0.27 | 0.66 | 0.03 | -0.01 | -0.35 | 0.02 | 1.00 | | | | | | | | | | | |
| **P** | 0.49 | 0.14 | 0.02 | -0.15 | -0.23 | 0.21 | 0.26 | 0.47 | -0.14 | 0.20 | 0.12 | 0.69 | -0.06 | -0.26 | 1.00 | | | | | | | | | | |
| **Pb** | 0.41 | 0.47 | -0.05 | 0.45 | -0.18 | -0.09 | 0.30 | 0.42 | -0.45 | 0.31 | 0.10 | 0.71 | 0.57 | -0.16 | 0.43 | 1.00 | | | | | | | | | |
| **Pr** | 0.65 | 0.45 | 0.07 | 0.44 | 0.07 | 0.01 | 0.58 | 0.66 | -0.20 | 0.28 | 0.13 | 0.72 | 0.56 | 0.10 | 0.45 | 0.85 | 1.00 | | | | | | | | |
| **Rb** | 0.13 | -0.19 | 0.68 | -0.22 | 0.79 | -0.13 | 0.08 | 0.30 | 0.81 | -0.09 | -0.09 | -0.34 | -0.13 | 0.73 | -0.06 | 0.02 | 0.22 | 1.00 | | | | | | | |
| **Sc** | 0.54 | 0.85 | 0.06 | 0.65 | -0.02 | 0.22 | 0.14 | 0.52 | -0.44 | 0.49 | 0.28 | 0.57 | 0.69 | 0.03 | 0.19 | 0.65 | 0.67 | -0.19 | 1.00 | | | | | | |
| **Sr** | 0.40 | 0.90 | 0.11 | 0.72 | -0.03 | 0.21 | 0.02 | 0.38 | -0.47 | 0.56 | 0.27 | 0.45 | 0.73 | 0.02 | 0.06 | 0.57 | 0.54 | -0.21 | 0.94 | 1.00 | | | | | |
| **U** | 0.38 | 0.33 | -0.45 | 0.58 | -0.29 | -0.02 | 0.51 | 0.26 | -0.65 | 0.19 | 0.08 | 0.83 | 0.64 | -0.22 | 0.35 | 0.66 | 0.73 | -0.36 | 0.61 | 0.51 | 1.00 | | | | |
| **V** | 0.82 | 0.15 | 0.72 | -0.30 | 0.45 | 0.50 | 0.27 | 0.91 | 0.56 | 0.06 | 0.23 | 0.05 | -0.23 | 0.39 | 0.34 | 0.22 | 0.45 | 0.55 | 0.24 | 0.11 | -0.09 | 1.00 | | | |
| **Ti** | 0.75 | 0.47 | -0.12 | 0.42 | -0.28 | 0.34 | 0.54 | 0.64 | -0.48 | 0.23 | 0.21 | 0.78 | 0.46 | -0.27 | 0.43 | 0.68 | 0.73 | -0.28 | 0.70 | 0.58 | 0.70 | 0.38 | 1.00 | | |
| **S** | -0.12 | -0.18 | 0.22 | -0.70 | -0.06 | 0.18 | -0.61 | -0.06 | 0.25 | -0.17 | -0.01 | -0.41 | -0.70 | -0.10 | 0.17 | -0.28 | -0.40 | 0.05 | -0.35 | -0.33 | -0.48 | 0.06 | -0.47 | 1.00 | |
| **TOC** | -0.56 | -0.24 | -0.24 | -0.21 | -0.18 | -0.27 | -0.40 | -0.58 | -0.13 | -0.19 | -0.12 | -0.25 | -0.23 | -0.17 | 0.00 | -0.26 | -0.46 | -0.22 | -0.34 | -0.26 | -0.21 | -0.52 | -0.47 | 0.40 | 1.00 |

B

| | Al | Ca | Fe | Mn | P | Ti | Fe/Ca | Mn/Fe | Fe/Mn | Fe/P | Th/U |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Al** | 1 | | | | | | | | | | |
| **Ca** | 0.36 | 1.00 | | | | | | | | | |
| **Fe** | 0.95 | 0.52 | 1.00 | | | | | | | | |
| **Mn** | 0.46 | -0.35 | 0.38 | 1.00 | | | | | | | |
| **P** | 0.49 | 0.02 | 0.47 | 0.69 | 1.00 | | | | | | |
| **Ti** | 0.75 | -0.12 | 0.64 | 0.78 | 0.43 | 1.00 | | | | | |
| **Fe/Ca** | 0.34 | -0.60 | 0.24 | 0.67 | 0.39 | 0.51 | 1.00 | | | | |
| **Mn/Fe** | -0.27 | -0.72 | -0.39 | 0.69 | 0.31 | 0.27 | 0.44 | 1.00 | | | |
| **Fe/Mn** | 0.08 | 0.68 | 0.19 | -0.50 | -0.24 | -0.42 | -0.28 | -0.59 | 1.00 | | |
| **Fe/P** | 0.38 | 0.55 | 0.47 | -0.37 | -0.52 | 0.05 | -0.15 | -0.71 | 0.61 | 1.00 | |
| **Th/U** | -0.06 | 0.44 | 0.09 | -0.15 | 0.14 | -0.09 | -0.33 | -0.26 | 0.27 | -0.05 | 1.00 |