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A palaeohydrological record of a complete Eemian series from Żabieniec Ża-19 (Garwolin Plain, Central Poland) with reference to palaeoclimate data

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ABSTRACT:

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The aim of this study was to reconstruct the evolution of the Eemian palaeolake in the Żabieniec site (Garwolin Plain, Central Poland); it identifies changes in the water level and the trophic status of the lake resulting from pan-regional factors, including climate changes occurring during individual phases of the last interglacial, and local geologic-geomorphological factors shaping the palaeoenvironment using multi-proxy methods (palaeobotanical analyses, subfossil Cladocera and diatoms analyses as well as determinations of the stable isotopes). A record was obtained of all seven Regional Pollen Assemblage Zones (RPAZs) according to Mamakowa's description of the Eemian pollen succession (1989), and of the changes in microfossil assemblages and isotopes in palaeolake sediments associated with lake evolution. Special attention was paid to the Middle Eemian RPAZ 4 (i.e. hazel phase) of the climatic optimum; all proxies associate this with the highest water level and a warm humid climate. During the E5/E6 RPAZs, the eutrophic lake transformed very quickly, and a transitional peatbog was formed. The higher humidity of the late Eemian resulted in another increase in water level. The multi-proxy record of the Żabieniec palaeolake which we obtained was compared to those of other Eemian water bodies in the Garwolin Plain and in Central Poland that exhibit sedimentation gaps especially during the younger part of the E5 RPAZ.

Key words: Eemian Interglacial; Fossil lake; Multi-proxy analyses; Climate changes, Central Poland.

INTRODUCTION

The biogenic lake and peat bog fossil deposits that accumulated during the interglacials have become extremely valuable archives of the changes in the natural environment that occurred during these times. Their contents can be used to reconstruct various features of the environment and provide an insight into climate change. The Eemian Interglacial, corresponding to the MIS 5e isotopic oxygen stage (Shackleton *et al.* 2002; Cohen and Gibbard 2011), remains beyond the reach of radiocarbon dating; as such, apart from exceptional situations when the sediments are varved (e.g. Lauterbach *et al.* 2012), the only way to determine the chronology of the core and perform a relative dating of the sediments from this period is palynological analysis. In Poland, the biogenic sediments of the Eemian interglacial have been studied in detail since the 1980s, where several hundred sites have been examined palynologically; the results of which have been used to plot Eemian isopollen maps, among others (Kupryjanowicz *et al.* 2018). The palynostratigraphic picture of the Eemian Interglacial in Poland was outlined by Mamakowa (1989), and later detailed by Kupryjanowicz and Granoszewski (2018). The findings correlate very closely with other records of the Eemian successions of Western Europe. Among the Polish sites of Eemian lacustrine sediments, several have been developed by high-resolution sampling, thus allowing climatic oscillations to be tracked (e.g., Granoszewski 2003; Kupryjanowicz 2008; Kołaczek *et al.* 2012; Malkiewicz 2018; Mirosław-Grabowska *et al.* 2018).

Such works also concern the studied region of the Garwolin Plain (Bober *et al.* 2021; Pidek *et al.* 2021a,b, 2022; Zalat *et al.* 2021). Although the problem of hydrological change has been discussed less often, it has been discussed nonetheless: as the environmental processes taking place in the Eemian interglacial were free of human intervention, any data from these periods can provide a valuable insight into the natural course of hydrological changes in reservoirs, from the moment of their formation to their disappearance. However, Eemian palaeohydrological studies are also increasingly common (e.g., Pawłowski 2011; Niska 2015; Suchora *et al.* 2022). A new perspective on the variability of the ecological status of the Eemian lakes, and further potential for their analysis, is offered by works on the development of the lake in Bispingen (Germany). The sediments filling the lake basin demonstrate well-preserved annual laminae, which makes it possible to precisely determine the duration of subsequent palynostratigraphic phases during the period (Lauterbach *et al.* 2012). Other significant studies concern the area of the Eemian Lake District in Poland (Klatkowa 1990; Bruj and Roman 2007). Among these palaeolakes there are Eemian sites of the Garwolin Plain.

Detailed palaeohydrological reconstructions require the use of a multi-proxy approach, which is not always possible in interglacial sediments. Nevertheless, the development of the lakes of this period can be reconstructed by various analyses, such as those examining fossil assemblages of Cladocera and diatoms (e.g. Zalat *et al.* 2021, Suchora *et al.* 2022), plant macroremains (Hrynowiecka *et al.* 2021), or geochemical analyses including those based on stable isotopes of carbon (C) and nitrogen (N) (Mirosław-Grabowska *et al.* 2015, Roman *et al.* 2021).

One approach currently at the forefront of palaeohydrological study is Cladocera fossil fauna analysis. In Poland, the Eemian Cladocera have been examined in around 20 sites, and the resulting palaeohydrological reconstructions have been presented in several publications.

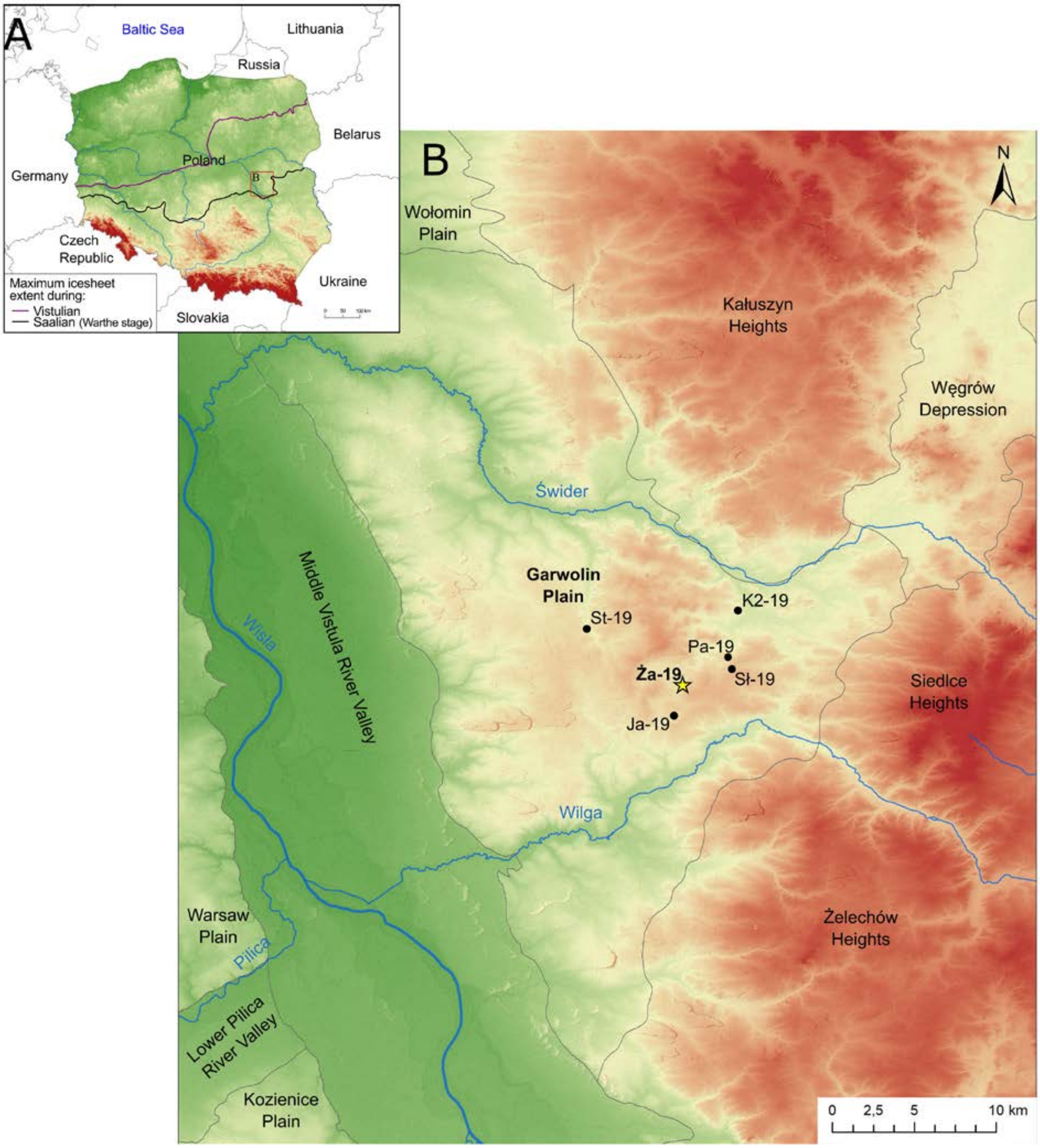
Even so, the small number of detailed palaeohydrological reconstructions from the Eemian interglacial underlines the need to intensify research in this direction. As such, detailed analyses are key to understanding the problem of hydrological change occurring under the influence of natural factors alone. By obtaining detailed reconstructions of the hydrological changes taking place during the interglacials, and correlating these findings with the better known evolution of the Holocene objects exposed to strong anthropopressure, it is possible to gain an important insight into the impact of human activity on these extremely valuable and sensitive ecosystems.

The present work aims to reconstruct the hydrological changes taking place in the Eemian interglacial based on the study of fossil biogenic sediments of a lake and peat bog site discovered in the village of Żabieniec on the Garwolin Plain (Central Poland). Geological, palaeogeographical, and palaeoecological research (Pidek *et al.* 2022) indicates the presence of three separate fossil reservoirs with Eemian sediments at the site under study. The results of the palynological analyses (Pidek *et al.* 2022) are accompanied by a reconstruction of the climatic conditions in the Eemian interglacial based on contemporary pollen analogues for all cores of Eemian organogenic sediments from the Żabieniec site: these findings include data from two cores obtained from the main, deepest lake basin (Ża-0 and Ża-19) and two from two smaller and shallower reservoirs (cores Ża-1 and Ża-2).

A pilot core (marked Ża-0) was used as material for palynological and plant macroremains analyses. Due to its very long fossil record, encompassing the decline of the Late Saalian, the Eemian interglacial, with all the Eemian phases according to Mamakowa (1989), and the Early Vistulian, the studied palaeolake turned out to be eminently suitable for detailed study. For this purpose, a new Ża-19 core was sampled; it was found to have a greater thickness of organogenic sediments than in the pilot core Ża-0, and therefore was subjected to high-resolution multiproxy analysis.

STUDY AREA

The palaeolake in Żabieniec is located in Central Poland, on the eastern side of the Garwolin Plain, which belongs to the Central Masovian Lowland, an area that forms part of the vast province of the Central European Lowland (Solon *et al.* 2018). This site is located on the southern edge of the vast Eemian Palaeo Lake District, the same as the extent of the Saalian glaciation (Bruj, Roman 2007). The re-survey of the Detailed Geological Map of Poland (Garwolin sheet in the scale of 1: 50,000) entailed the discovery of new sites of Eemian lake deposits, including the discussed Żabieniec palaeolake (Żarski 2020).



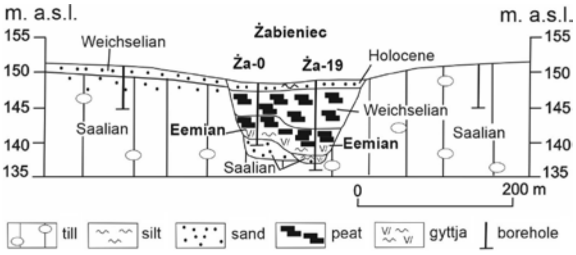
Text-fig. 1. Study area: A – the region of the Garwolin Plain in Poland; B – Żabieniec site and other Eemian paleolakes mentioned in the text.

Previous studies have already examined the palaeoenvironments of many palaeolakes in the Garwolin Plain, next to the Żabieniec site (Ża-19): Jagodne Ja-19 (Bober *et al.* 2021), Kozłów K2-19 (Pidek *et al.* 2021b; Suchora *et al.* 2022), Słup Sł-19 (Kultys *et al.* 2023), Struga St-19 (Zalat *et al.* 2021). The Żabieniec site itself consists of three separate fossil lake basins filled with Eemian deposits of different thickness; all of which have been investigated by pollen analytical methods (Hrynowiecka *et al.* 2020; Pidek *et al.* 2022, Hrynowiecka *et al*. submitted). These objects are located in the interfluve of the Wilga and Świder rivers: the left-hand tributaries of the Vistula (Text-fig. 1B).

MATERIALS AND METHODS

The research material consisted of biogenic sediments from the deepest lake basin at the Żabieniec palaeolake site. In the sediments of two cores (Ża-0 and Ża-19), whose geological situation is illustrated in Text-fig. 2, the palaeoclimate record has already been reconstructed using modern pollen analogues and PPPbase software (Pidek *et al.* 2022). The reconstructed succession of vegetation indicates a record of all seven phases of the Eemian interglacial period, i.e. Regional Pollen Assemblage Zones (RPAZs), numbered E1–E7 (Mamakowa 1989). The impressive length of the palaeoenvironmental record in the Ża-19 core also allowed for the detection of probable sedimentary breaks and inferences about their causes (Hrynowiecka *et al*. submitted). Although both cores contain biogenic sediments formed from gyttjas and peats, their thickness differs because Ża-19 was collected in the deepest part of the palaeolake and Ża-0 was collected closer to the shore. The Ża-19 core is therefore excellent material for conducting detailed research on the hydrological changes of the Eemian interglacial. In the bedrock of the palaeolake deposits, glacial till occurred (Text-fig. 2).

Biogenic sediment core Ża-0 was collected in 2016 using a 5.0 cm-diameter geoprobe corer, while Ża-19 was collected with a 4.8 cm-diameter power-probe corer. The cores were secured for transport in plastic foil. In the laboratory, the material was divided into 5 cm sections (Ża-0) or 1 cm sections (Ża-19) to facilitate high-resolution analyses.



Text-fig. 2. Geologic-geomorphologic situation of the studied fossil Eemian deposits in Żabieniec.

Pollen analysis

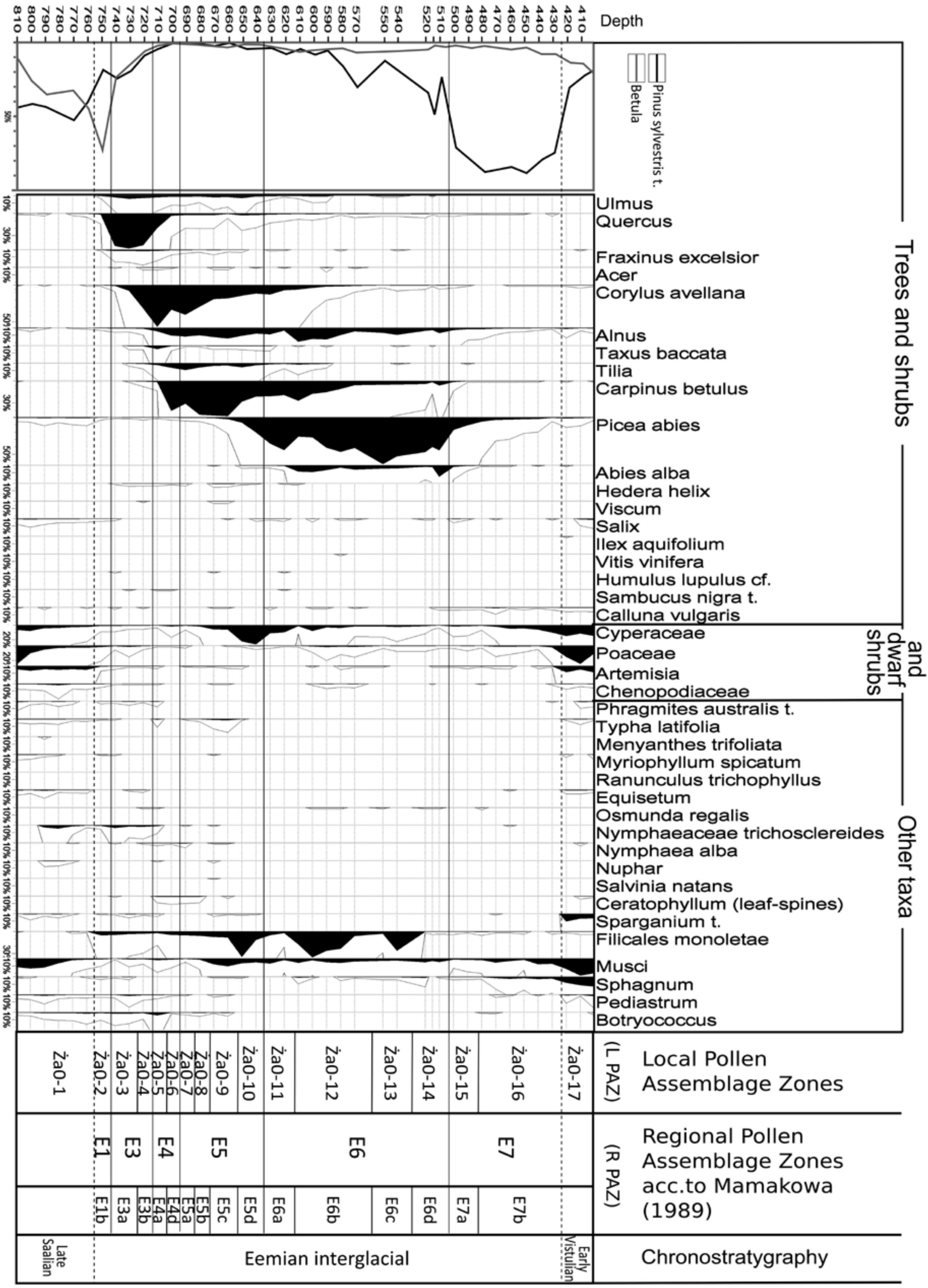
Samples (2 cm3) were obtained for pollen analysis at 5 cm intervals from the Ża-19 core (78 samples from the depth of 7.00–11.05 m, with the exception of the Early Vistulian part of the core 7.00–7.30 m where the depth interval was 10 cm) (Table 1). In the pilot core Ża-0 41 samples were obtained from the depth of 4.00–8.10 m at 10 cm intervals, with the exception of one interval of 5 cm where sharp boundaries between zones were detected and two samples with the interval of 20 cm. The samples were treated in the laboratory according to standard palynological procedures (Berglund and Ralska-Jasiewiczowa 1986). The biogenic sediments were treated with HCl, KOH, HF, and Erdtman's acetolysis (1960). Pollen spectra were counted under a NIKON ECLIPSE E600 light microscope at a magnification of 400–600x on at least two slides with an 18×18 mm coverslip. The mean terrestrial pollen count (AP+NAP) was 700–800 per sample. Percentage pollen diagrams (Text-figs 3, 4) were plotted using POLPAL software (Nalepka and Walanus 2003).

Cladocera analysis

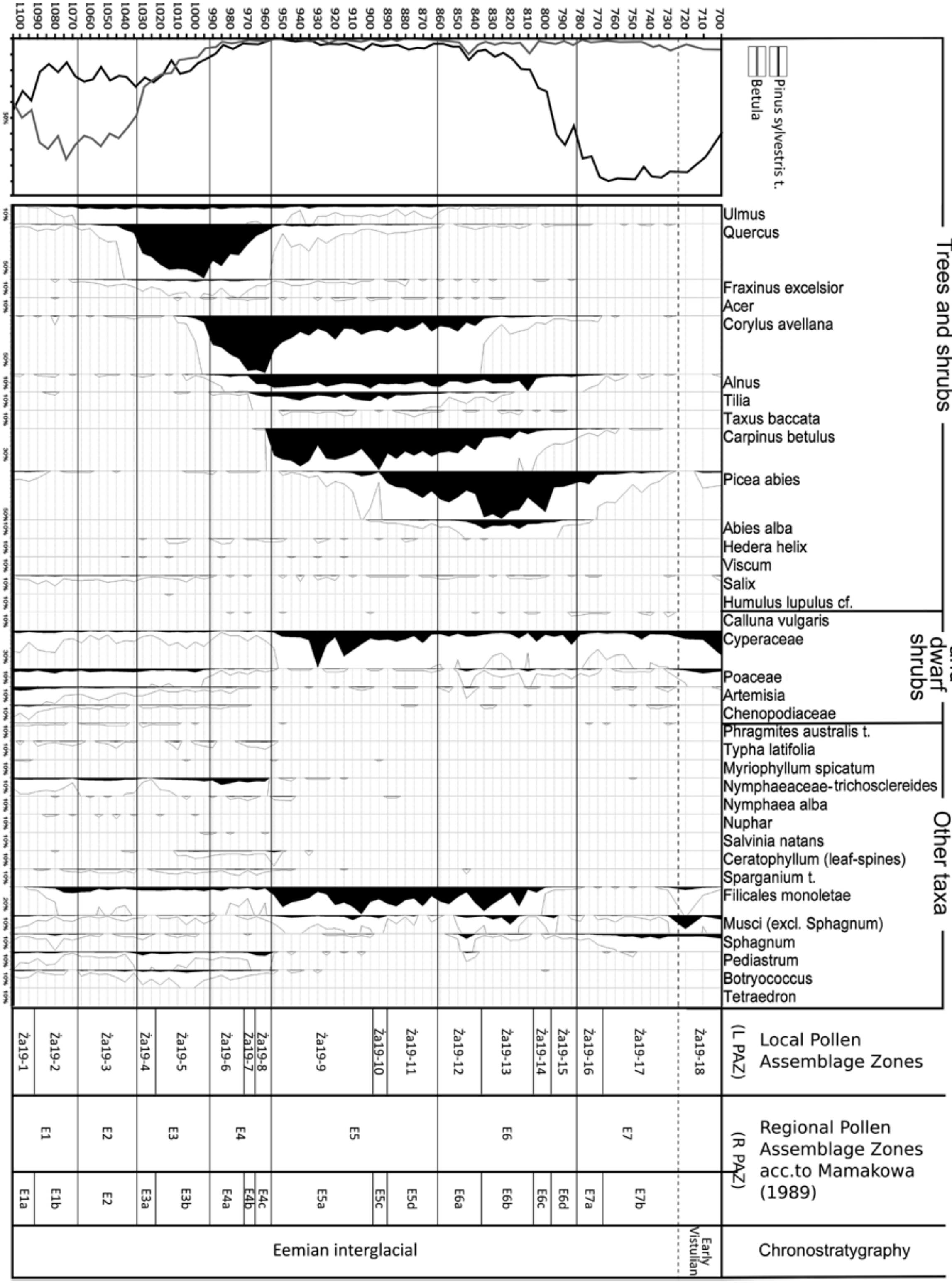
The Cladocera remains were analyzed in 41 samples from core Ża-19 (profile length – 4 m) using a modified treatment of metod by (Frey 1986). Briefly, 1 cm^3 of each sample was decalcified (with 10% HCl), soaked overnight, and washed with distilled water on 33 μm mesh. It was then slowly heated in 10% KOH (60–100°C, but not reaching the boiling point) while being gently stirred with a glass rod. Afterward, ultrasonic treatment (15 minutes) was applied. Next, after another warm KOH treatment with a distilled water sieve (33 μm), all residues were transferred quantitatively to scaled test tubes, and topped up to 10 ml volume. All Cladocera remains (shells, headshells, postabdomens, postabdomenal claws, ephippia) were identified under 100–600x magnification in a compound light microscope (MBL 800). Between two and five slides were examined for each sample to exceed the minimum counting sum of 150 (Kurek *et al.* 2010). Species were identified using the Cladocera atlas (Szeroczyńska and Sarmaja-Korjonen 2007). The group of small Cladocera included: *Alona rectangula,*

RPAZ no and name	Characteristics
E1 *Pinus–Betula*	Maxima of birch and then pine pollen, reflect the natural succession of pioneering birch and pine-birch forests in the protocratic phase of the interglacial. The lake was surrounded by pine and woody birch but still demonstrated a significant proportion of NAP, suggesting the presence of open herbaceous communities in the landscape. Pollen from *Salix*, *Cyperaceae*, *Filipendula* (*F. ulmaria*?), *Thalictrum* and *Galium* t. were found, together with spores of brown mosses and *Sphagnum*, all of which were probably derived from wet habitats around the lake. Drier areas were occupied by communities of juniper, grasses, *Artemisia*, *Chenopodiaceae* and *Anthemis*. Aquatic vegetation was represented by *Nymphaeaceae* and *Ceratophyllum* species, as well as *Pediastrum*, *Botryococcus* and *Tetraedron algae. The reedswamps surrounding the palaeolake consisted of Sparganium, Phragmites,* and *Typha*. Brown mosses and some *Sphagnum*, possibly in a mosaic with sedges, were growing near the lake. The macrofossil diagram of the Ża-0 profile (Hrynowiecka *et al*. – submitted) is further enriched with the bryozoans *Cristatella mucedo* and seeds of *Najas marina*
E2 Pinus–*Betula* –Ulmus	Pioneering pine-birch communities still dominate, but in river valleys, they are quickly replaced by encroaching riverine forests formed by *Ulmus* and *Quercus* (probably *Quercus robur* acc.to Granoszewski 2003) and soon with an admixture of *Fraxinus*.
E3 *Quercus–Fraxinus–Ulmus*	A rapid decrease in the percentages of pine and birch can be seen, accompanied by an increase in *Quercus*, indicating the withdrawal of pioneering forests with these species. *Quercus* began to play a dominant role in the forests. At least two species of oak were present at that time (*Q. robur* and *Q. sessilis*). At the same time riverine communities of *Ulmus, Quercus* and *Fraxinus expanded*. Hazel arrived in the drier habitats after the withdrawal of birch. The aquatic and reedswamp vegetation was composed of the same taxa as before, but there was a slightly more abundant record of *Pediastrum, Botryococcus* and *Tetraedron* algae, together with more abundant pollen from *Typha latifiolia* t. and *Sparganium*, as well as various nympheids.
E4 *Corylus–Quercus–Tilia*	New *Alnus* and *Tilia cordata* trees entered the rich riverine multispecies communities, as well as dry ground forests composed of oak and hazel. *Corylus* pollen values reached a maximum at that time. In drier habitats, hazel could have formed patches of hazel thickets. Alder carrs started to spread in more waterlogged places, where yew also appeared. The macrofossil record of the Ża-0 profile (Hrynowiecka *et al.* – submitted) indicates the presence of new taxa requiring a milder climate, such as *Aldrovanda vesiculosa* and *Salvinia natans*, thus indicating significant warming. This corresponds with the pollen data (e.g. Text-fig. 3) that now contain a greater number of *Ceratophyllum* hairs, more abundant *Nymphaeaceae* trichosclereids and *Myriophyllum spicatum* pollen. The record of *Sphagnum spores is scarce.*
E5 *Carpinus–Corylus–Alnus*	A rapid increase in pollen values for *Carpinus betulus*; however, soon after the *Corylus* peak noted in the second half of the previous zone, traces of *Carpinus* and *Tilia* expansion can be seen. The main forest-forming tree during this time appears to be hornbeam, which, together with lime, formed communities that would have resembled contemporary Tilio-Carpinetum (*vide*: Matuszkiewicz 2001). *Picea pollen* values draw attention in this zone, as they have increased from the early hornbeam phase, which might indicate high humidity. This is also supported by other findings, such as the increased share of *Filicales monolete* and *Cyperaceae*. Hazel withdrew at this time, giving way to an expansion in *Carpinus*. Thermophilous shrubs and vines (*inter alia*: *Ilex aquifolium, Hedera helix* and *Humulus lupulus*) were present in the underwood. It is likely that spruce could also have occurred in alder carrs. However, the *Alnus* pollen values did not change, suggesting the survival of extensive alder-carr type communities. Wet meadow-like communities and sedge mires were sources of pollen from *Cyperaceae*, *Thalictrum Filipendula*, and partly *Apiaceae*; in addition, fern spores, including *Thelypteris palustris* (= *Dryopteris thelypteris*) were highly abundant. The share of spruce in the forests increased significantly at the end of the E5 RPAZ, together with the arrival of fir and pine, and a drop in lime and elm pollen. There are clear signs that the lake shallowed and a peatbog formed. Many macrophytes disappeared, including the most thermophilic taxa, *Najas minor* and *Najas marina*, distinguished during the previous period in the Ża-0 macrofossil diagram (Hrynowiecka *et al*. – submitted); in addition, most noteworthy planktonic taxa withdrew during this period. Also the pleustonic communities demonstrated a greater abundance of *Lemna trisulca*, preferring very shallow eutrophic lakes. *Cyperaceae* pollen values and the share of *Filicales monolete* spores increased significantly. A drastic reduction was found for *Nymphaeaceae*, *Myriophyllum spicatum*, *Ceratophyllum*, *Typha latifolia* and *Sparganium* in the pollen diagram, which indicate a clear change in aquatic and reedswamp vegetation
E6 *Picea–Abies*	*Picea abies* appeared to have a special role, as documented by its very high values in pollen diagrams. These are accompanied by an increase in the share of *Abies* and a simultaneous marked decline in *Carpinus*. Other thermophilic trees, shrubs and vines withdrew earlier. The plant macrofossil diagram in the Ża-0 profile indicates a clear change towards a fall in water level and oligotrophization of water, resulting from the formation of a transitional peatbog (Hrynowiecka *et al*. – submitted). *Rhynchospora alba*, *Scheuchzeria palustris* and *Carex diandra*, occurred. An increase in the share of sedges can be seen, e.g. *Carex elata* and *C. vesicaria*. The sclerotia of *Cenococcum geophilum*, gemmules of *Porifera*, and wood debris were highly abundant, suggesting the presence of a large supply of sediment washed from the banks of the lake; this may be due to an increase of the water level in the younger part of the E6 RPAZ
E7 *Pinus*	Dominance of pine forests marked a further gradual deterioration of climate conditions occurred in this declining part of the Eemian, as marked by the increasing *Pinus* pollen values. Initially, a significant admixture of *Picea* was present. This might have resembled the modern *Leucobryo–Pinetum* association with birch and spruce in admixture (Granoszewski 2003). The presence of increasing values of *Sphagnum* spores may indicate that in peatland areas, an admixture of spruce may have led to formation of spruce-pine boreal forest. At that time, herbaceous communities also developed. However, plant macroremains are very scarce in the Ża-0 core during the late E6 and E7(Hrynowiecka *et al*. – submitted). A single fragment of *Myriophyllum* spines was found, which together with the increasing values for *Pediastrum*, indicate a rise in water level. A record of brown moss shoots can be seen, as well as the remains of sedges, e.g. *Carex riparia, C. elata* and *C. vesicaria*.

Table 1. Characteristics of RPAZs in the Ża-19 and Ża-0 profiles.



Text-fig. 3. Simplified percentage pollen diagram of the Ża-0 profile.



Text-fig. 4. Simplified percentage pollen diagram of the Ża-19 profile.

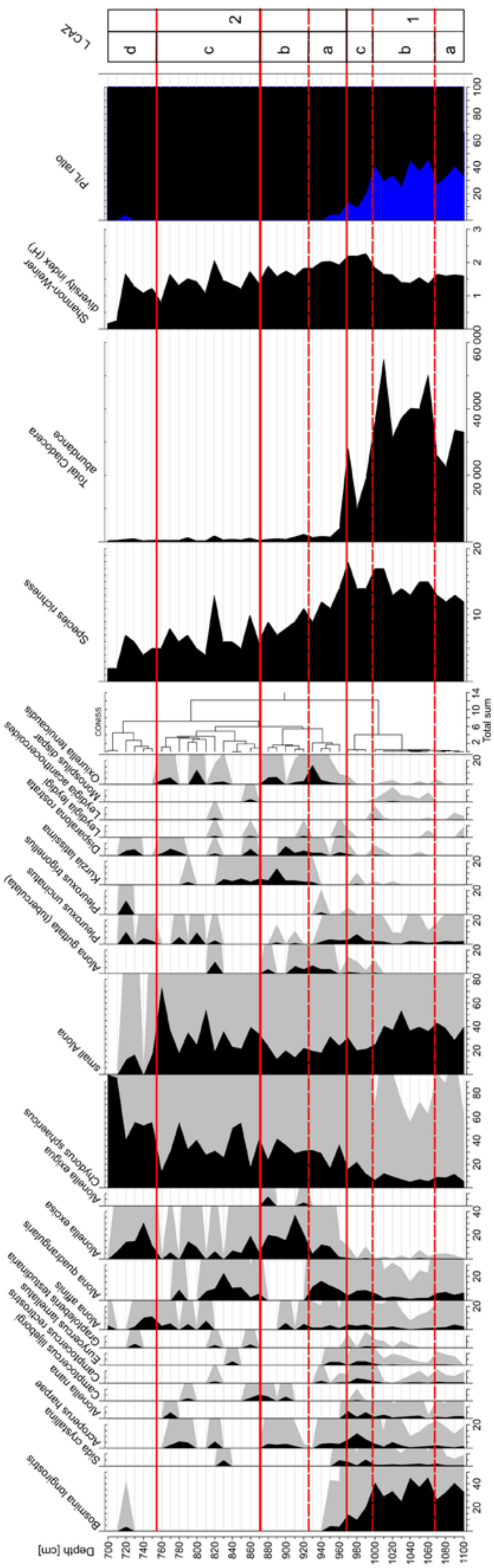
Alona guttata (*Alona guttata* tuberculate counted separately). Results were presented as percentage diagrams (Text-fig. 5), P/L ratio (relative abundance of planktonic to littoral taxa), total Cladocera abundance, species richness (*n*) and Shannon-Weiner diversity index (*H'*) (Szeroczyńska 1998; Flößner 2000; Błędzki and Rybak 2016). Above the depth of 960 cm only *Bosmina longirostris* was designated as an open-water species (Table 2). Cladocera Assemblage Zones (CAZ) were delineated based on CONISS cluster analysis (Tilia Graph, 171 Grimm 2011). Ecological diversity measures were calculated by means of PAST software (Hammer *et al.* 2001).

Any other microfossils or plant remains observed during the analysis of the Cladocera fossil remains were also counted such as *Ceratophyllum* hairs, *Nymphaeaceae* trichosclereids and fern spores. In addition, animal remains such as head capsules of *Chironomidae* spp. (species were not specified), *Rotifera* eggs and *Turbellaria* cocoons were recorded, as well as fungi, such as sporangia of *Glomus*, *Microthyriaceae* and *Alternaria* spp. These results were converted into the number of individual microfossils in a 1 cm^3 volume of residue and presented in a diagram (Text-fig. 6). They were determined according to van Geel (1978); Haas (1996); de Klerk *et al.* (2009); Shumilovskikh and van Geel (2020) and the non-pollen database at (https://non-pollen-palynomorphs.uni-goettingen.de/).

Diatom analysis

Diatom analysis was performed on 28 sediment samples obtained from palaeolake sediments within the depth interval 960–1100 cm in the Żabieniec Ża-19 core. In each sample, fossil diatoms were extracted from 1 g of dry sediment by HCl and H_2O_2 digestion as described by Zalat and Servant-Vildary (2007). For slide preparation, 0.1 ml of the final suspension was dried on coverslips and then mounted onto glass slides using Naphrax ® (R.I = 1.74) for microscope observation. Diatoms were identified at the species level using an Optika light photomicroscope under oil immersion at 1000× magnification, with a digital camera equipped with differential interference (DIC) optics.

The identification of a diatom species, and its ecological characteristics, was based upon published works (e.g., Krammer and Lange-Bertalot 1986–1991; Denys 1991–1992; van Dam *et al.* 1994; Metzeltin and



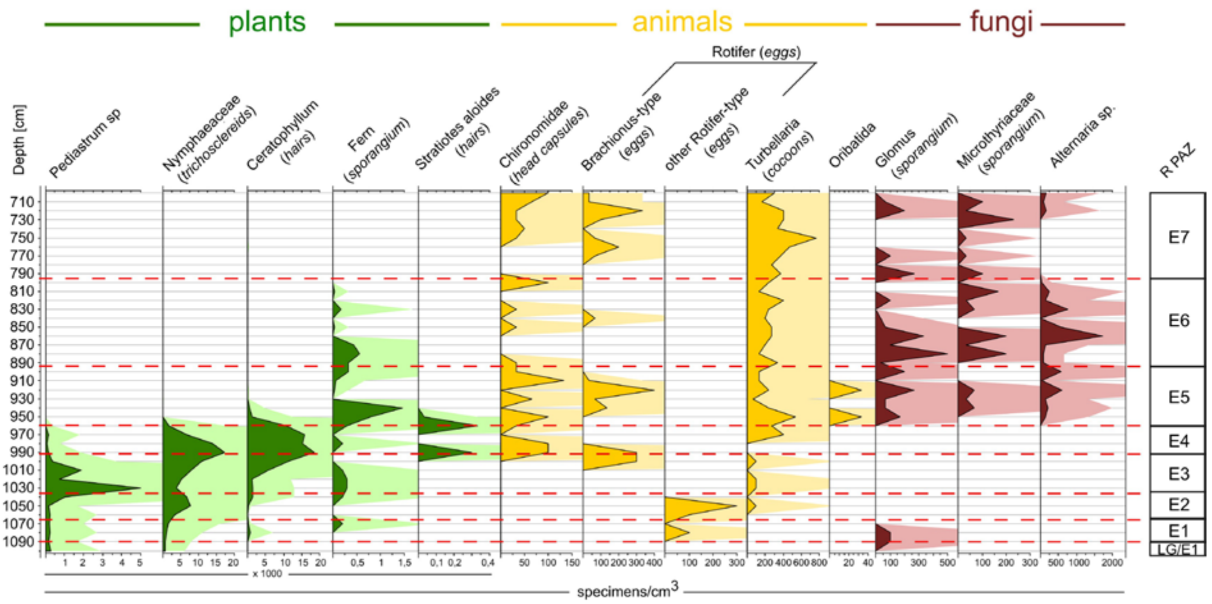
Text-fig. 5. Taxonomic composition and diversity indices of Cladocera: species richness, total abundance, Shannon-Weiner diversity index and P/L ratio and Local Cladocera Assemblage Zones (L CAZ).

Phase/ subphase	Sample depth [cm]	Description
1	970–1100	Phase associated with lake development, with the proportion of planktonic species reaching 46%. This phase is also dominated by taxa included in the small *Alona* taxonomic group. High species richness and a low Shannon-Weiner dominance index (H' min- 1.4, max -2.3) (Text-fig.5). This phase is divided into three subphases.
1a	1070–1100	Subphase characterised by the dominance of the planktonic species *B. longirostris* (max 40.9%), the small *Alona* group (max 43.9), and the broadly environmentally-tolerant taxon *Chydorus sphaericus*. The proportion of *A. affinis* (4.5%) and *Alona quadrangularis* (max 7.7%) is also high.
1b	1000–1060	Subphase characterised by the highest total abundance (max 55,050) of the Cladocera fauna and the highest species richness (max 18 taxa). In this phase, *B. longirostris* achieves the highest percentage share (max 46%) and is the only planktonic species. A significant proportion is also achieved by small *Alona (max 54.5%). The proportion of A. affinis* (min 0.7%) and *A. quadrangularis* (min 1.5%) decreases. Only in this subphase does *M. dispar* (max 1.3%) make a continuous contribution.
1c	970–990	Subphase characterised by a decrease in total abundance (min 10 250 spec./cm^3) and decrease in species richness (min 14 taxa). The only open-water species present is *B. longirostris*, whose proportion drops to 9.8%. There is a significant increase in the proportion of *C. sphaericus*, *A. quadrangularis*, *P. uncinatus*, *A. harpae*, *S. crystallina.*
2	700–960	Phase marked by the disappearance of *B. longirostris*. Species richness and total abundance decrease significantly.
2a	930–960	Subphase marked by a decrease in the proportion of *B. longirostris, and its eventual disappearance. Dominant taxa include Ch. sphaericus* (max 37.6%) and the group of organisms classified as small *Alona* (max 32.3%). Benthic species, e.g. *A. quadrangularis* (max 16.5%), are significantly expanding. Vegetation-associated species found in peatlands are also encroaching: *A. excisa* (max 12.4%), *D. rostrata* (max 2.5%), *O. tenuicaudis* (max 4.1%). *A. guttata* (*ver tuberculata*) also enters this phase (max 7.1%).
2b	870–920	Subphase dominated by: *A. excisa* (max 37.9%), *Ch. sphearicus* (max 42.9%) and a group of small *Alona* (max 34.3%). The acidophilic bog species *C. lilljeborgi* (Błędzki and Rybak 2016) (max 5.7%) enters, with some examples of *A. exigua*. The proportions of species associated with marsh and peatland habitation remain continuous: *K. lattisima* reaching a maximum share (max 14.5%), *D. rostrata* (max 8.2%) and *O. tenuicaudis* (max 6.1%).
2c	760–860	In this subphase, only littoral species are present. The dominant species are *Ch. sphaericus* (max 56.3%), small *Alona* (max 75.5%) and *A. excise* (max 15.4%). In this subphase, the benthic species *A. quadrangularis* returns, reaching a maximum (23.7%) in the middle of the phase and disappearing at the end of the subphase. Towards the end of the subphase, the species associated with vegetation *A. affinis* appears (max 5.7%). Peatland species such as C. lilljeborgi, *K. lattisima* and *O. tenuicaudis* disappear.
2d	700–750	Nine species present in this subphase, which is characterised by low total abundance (max 983). The only planktonic species*, B. longirostris* (max 4.2%), appears only in one sample. The subphase is dominated by *Ch. sphaericus*, which reaches 96% by the end of the phase. Dominant taxa also include *A. excise* (max 31.6%) and the small *Alona* group (max 16.9%). The subphase also includes *A. affinis (max 11.8%) and G. testudinaria* (max 3.4%) living among the vegetation. In addition, *P. uncinatus* (max 10.4%) is observed, as well as *P. trigonellus* (max 12.5%), which occurs episodically, and *D. rostrata* (max 5.1%).

Table 2. Characteristics of the Cladocera microfossil analysis.

Lange-Bertalot 1998; Witkowski *et al.* 2000; Hofmann *et al.* 2011; Zalat *et al.* 2022). The diatom concentration was calculated by adding a known concentration of synthetic microspheres to the samples; the result was expressed as valves per gram of dry weight (dwg) sediment (Battarbee and Kneen 1982). Recent taxonomic advances have split many diatom taxa of the former genus *Fragilaria* sensu lato into several new genera, comprising *Fragilaria*, *Pseudostaurosira*, *Staurosira*, and *Staurosirella* (Williams and Round, 1987). *Cyclotella* sensu lato taxa include the genera: *Cyclotella*, *Discostella*, *Punctitulata*, *Pantocsekiella* and *Lindavia*.

In every diatom-rich slide, 1000 diatom valves were counted at 1000x magnification and subjected to statistical analysis to estimate the percentage abundance of individual taxa. For samples with low diatom concentrations, at least 300 valves were counted. The relative frequencies of each species were calculated as a percentage of total diatom valves (%TDV) counted in each sample to estimate environmental parameters such as life form-grouping, pH and salinity spectrum. Diatom ecological groups were differentiated by multivariate statistical analysis using PAST v.4.03 software (Hammer *et al.* 2001). Only diatom taxa with a relative abundance over 3% of total diatom valves in at least three samples were included in the calibration model. The



Text-fig. 6. Diagram of the total number of the selected NPP taxa determined along with the Cladocera microremains.

diatom zones (Table 3) were distinguished by cluster analysis based on a Euclidean distance measure and constrained clustering.

Analysis of stable isotopes

The organic sediments from the Ża-19 profile were tested for organic carbon and nitrogen concentrations and stable carbon and nitrogen isotopes. The analyses for carbon and nitrogen isotopes were performed on 40 samples (depth 728–1101 cm) of organic sediments. The sediments were dried at 60°C, ground and treated with hydrochloric acid to remove the carbonate fraction (Ku *et al.* 2007; Mirosław-Grabowska *et al.* 2015). The carbon and nitrogen isotope compositions were analysed using a Flash Elemental Analyzer 1112 and a Thermo MAT 253 mass spectrometer, which were calibrated based on an internal nicotinamide standard and reported as per mill (‰) deviations versus atmospheric N_2 ($\delta^{15}N$) and Vienna Pee Dee Belemnite ($\delta^{13}C$). The carbon and nitrogen isotope ratios are presented as curves of variation of $\delta^{13}C$ and $\delta^{15}N$. The analytical

Phase/ subphase	Sample depth [cm]	Description
DZ. 1	1070–1095	A distinct increase in the abundance of warmth-loving small planktonic *Cyclotella sensu lato* species (68–73% of the total diatoms) with a marked decline in cold-loving *Fragilaria sensu lato* taxa (4.7–7.7%). *Pantocsekiella comensis*, *Pantocsekiella delicatula,* and *Pantocsekiella ocellata* were dominant, while *Cyclotella cyclopuncta*, *Cyclotella distinguenda,* and *Lindavia radiosa*, were frequently observed. A well-preserved and high diatom concentration is characteristic of this zone. The planktonic diatoms were most dominant than the periphytic forms.
DZ. 2	1035–1065	The zone distinguished by a reduction in the abundance of planktonic cyclotelloid taxa (19–24%), together with an obvious shift in the dominant fragilarioid species (33–53%). *Staurosira inflata* was the most common species, associated with the frequent occurrence of *Staurosira construens*, *Staurosira construens* var. *triundulata,* and *Fragilaria istvanffyi*. The epiphytic *Cymbellafalsa diluviana was observed commonly. The periphytic taxa are more dominant than the planktonic forms. The mean concentration of diatom valves decreased markedly.*
DZ.3	1025–1035	The zone characterized by an abrupt marked decline in diatom concentration with a decreasing abundance of both *Fragilaria sensu lato* and *Cyclotella sensu lato* species. The periphytic taxa predominated in this zone (93–94%). The benthic *Pinnularia* species associated with the epiphytic *Cymbopleura* taxa were common.
DZ.4	960–1020	The zone characterized by the sporadic occurrence of diatom taxa that are mainly represented by fragmented frustules of large benthic pennate diatoms of *Pinnularia* species associated with irregular distribution of *Cymbellafalsa diluviana* and *Cymbopleura* spp.

Table 3. Characteristics of the diatom assemblage zones of the Ża-19 profile.

errors (1 SD) for the δ^{13}C and δ^{15}N measurements were 0.17‰ and 0.24‰, respectively. Isotopic analyses were performed in the Stable Isotope Laboratory at the Institute of Geological Sciences of the Polish Academy of Sciences in Warsaw, Poland.

Determination of the organic and mineral matter contents

To determine the proportions of organic matter (LOI550) and carbonates (LOI950), a loss-on-ignition analysis was performed. Eighty samples of lake sediments were selected, dried and homogenised in a grinder. The resulting material was then heated sequentially at 550°C for 4.5 hours and 950°C for two hours (Myślińska 2001). Each time the crucibles cooled in the desiccators, the material was weighed on a laboratory balance to the nearest thousandth of a gram. The percentage content of organic matter and carbonates were calculated using MS Excel (Microsoft).

RESULTS OF MULTI-PROXY ANALYSES

Pollen analysis

The palynological results are presented as Table 1 with characteristics of Regional Pollen Assemblage Zones typical for both Ża-19 and Ża-0 cores, and abbreviated pollen diagrams (Text-figs 3, 4; Table 1). Local Pollen Assemblage Zones in both the pollen diagrams record the same vegetation history and are correlated to RPAZs (acc. to Mamakowa 1989) and to subzones according to the classification by Kupryjanowicz and Granoszewski (2018). Vegetation history reconstructed on the basis of both the cores is abbreviated in Table 1 with references to detailed interpretation by Hrynowiecka et al. (submitted). The pollen record bears all typical features of the Eemian pollen succession and encompasses also a part of the Early Vistulian.

In the Ża-0 profile a record of the Late Eemian/ Early Vistulian transition can also been seen above the depth of 420 cm, while in the Ża-19 the boundary lies at the depth of 710 cm. This end of the interglacial was marked by an increase in climate humidity, which resulted in a rise in groundwater level and the return of many taxa representing aquatic vegetation. *Callitriche autumnalis* and *Hippuris vulgaris* occurred in cool waters.

The first cooling of the Vistulian is often marked by the growth of open communities of herbaceous vegetation. *Pinus* probably withdrew completely from the vicinity of the palaeolake. In more humid areas, *Cyperaceae* and *Salix* dominated. In drier habitats, steppe communities with a high proportion of *Poaceae, Artemisia, Chenopodiaceae* and *Juniperus* spread (Hrynowiecka *et al*., submitted).

Cladocera

The analyses of the fossil Cladocera fauna allowed two phases of development to be identified. Phase L CAZ1 corresponds to the lake stage of the reservoir studied, and phase L CAZ2 to the peatland stage. Phase 1 was divided into three subphases (a–c), and phase 2 into four (a–d) (Table 2).

Non-pollen palynomorphs

The results of the non-pollen palynomorph analyses (NPPs), counted along with the Cladocera microremains, indicate high variability in the abundance of plant, animal and fungal remains. Only the selected NPPs from the total database at (https://non-pollen-palynomorphs.uni-goettingen.de/) were determined. These results were correlated with the regional pollen zones determined by palynological analysis (R PAZs E1–E7) (Table 4).

Diatoms

The analysis of the diatom zones identified obvious changes in diatom assemblages along the core section, which were characterized by clear shifts in genus dominance. The diatom taxa were abundant and generally well to moderately preserved through most parts of the core; however, some admixtures of mechanically-broken pennate diatom valves were observed in the upper part at a depth of 960–1095 cm. Variations in the ratio of planktonic to periphytic taxa were documented to reconstruct fluctuations in lake level over the deposition period.

The analysis also indicated that marked environmental and climate changes occurred at the Żabieniec site during the Eemian. Clear fluctuations in the diatom assemblage composition and variations in the relative abundances of diatom taxa can be seen along the core section over time, allowing the recognition of distinctive diatom zones corresponding to variations in the palaeolake water level related to climate changes. The most common and dominant diatom species in the examined samples were analysed stratigraphically, as shown in the enclosed figure (Text-fig. 7; Table 3).

Phase/ subphase	Sample depth [cm]	Description
LG/E1	1090–1100	The turn of the Late Saalian and the Eemian interglacial was characterized by a significant poverty of aquatic vegetation. The results of NPPs counted during the Cladocera analysis indicate the occurrence of only *Pediastrum* sensu lato (max. 2900 spec./cm^3) and *Nymphaeaceae* sclereids (max. 800 spec./cm^3). *Glomus* spores (max 100 spec./cm^3) were also recorded during this phase.
E1	1070–1080	Phase associated with significant development of aquatic vegetation. The abundance of *Pediastrum* (max. 2700 spec./cm^3) remains stable, while that of *Nymphaeaceae* sclereids (max. 1600 spec./cm^3) increases. *Ceratophyllum* trichomes (max. 700 spec./cm^3) and fern spores (max. 200 spec./cm^3) appear. Rotifera eggs (max. 100 spec./cm^3) were recorded in this phase for the first time. The abundance of *Glomus* spores (max. 100 spec./cm^3) continues.
E2	1040–1060	Phase associated with the continued development of aquatic vegetation, with a significant increase in *Pediastrum* (max 10,200 spec./cm^3), *Nymphaeaceae* sclereids (max 7,800 spec./cm^3), *Ceratophyllum* (max 1,300 spec./cm^3). This level is related to the next stage of animal development, *Rotifera* eggs increase (max 300 spec./cm^3), and *Turbellaria* cocoons appear (max 100 spec./cm^3). *Glomus* spores, on the other hand, are disappearing.
E3	990–1030	Phase related to the development of aquatic vegetation. The maximum (50,000 spec/cm^3) is reached by *Pediastrum*, the proportion of which then begins to decrease. There is an increase in the proportion of *Nymphaeaceae* sclereids (max 17,200 spec./cm^3) and *Ceratophyllum trichomes (max 18,700 spec./cm*^{3}) towards the end of the phase, where they reach their maxima. Fern spores persist continuously. *Stratiotes aloides* enters towards the end of the phase. *Turbellaria* cocoons (max 100 spec./cm^3) and *Rotifera* eggs (max 300 spec./cm^3) are still present in this phase. Towards the end of the zone, *Chironomidae* enter as indicated by presence of head-capsules.
E4	960–980	In this phase, the abundance of *Pediastrum* decreases significantly (max 1,900 spec./cm^3), which disappears towards the end of the phase, as does *Nymphaeaceae*. The abundance of *Ceratophyllum* trichomes and *Stratiotes aloides* fern spores and spikes remain at a similar level. The aquatic animals *Chironomidae* (max 100 spec./cm^3) and *Turbellaria* cocoons (max 400 spec./cm^3) develop intensively.
E5	900–950	Phase associated with the decline of macrophytes: *Ceratophyllum* and *Stratiotes aloides*. Fern spores reach a maximum. This level is associated with intensive animal growth: *Chironomidae* (max 100 spec./cm^3), *Rotifera* (max 400 spec./cm^3) and *Turbellaria cocoons* (max 533 spec./cm^3). Oribatid carapaces appear in this phase, but nowhere else. Phase E5 is also associated with intensive fungal growth, identified by the abundance of *Glomus, Microthyriaceae* and *Alternaria* spp. spores.
E6	800–890	In this phase, only ferns remain from the plants, with spores reaching their highest abundance at the beginning of the phase and disappearing completely towards the end. The abundance of *Chironomidae* decreases, and the *Rotifera* eggs are present in only one sample (840). *Turbellaria* cocoons continuously, with a maximum of 400 spec./cm^3 seen at a depth of 820cm. The E6 phase, on the other hand, is associated with intensive fungal growth. The maximum for the whole profile is reached by the abundance of *Glomus* spores (max 500 spec./cm^3). The abundance of Microthyriaceae then reaches 200 spores cm^{-3}.
E7	700–790	Phase associated with the development of the fauna. After a gap at the beginning of the zone, the abundance of *Chironomidae* head capsules (max 100 spec./cm^3) and *Rotifera* eggs (max 200 spec./cm^3) increases significantly. During this phase, at a depth of 750 cm, the maximum abundance for the whole profile is reached by *Turbellaria cocoons (max 766 spec./cm*^{3}). Of the fungi, only *Microthyriaceae* are still present, peaking at a depth of 730 (233 spec./cm^3). *Glomus* spores occur at the beginning of the phase, then disappear and reappear towards the end of the phase. *Alternaria* spp. are absent from the beginning of the phase, but reappear at depth 730 cm occurring until the end of the interglacial.

Table 4. Characteristics of the NPP analysis.

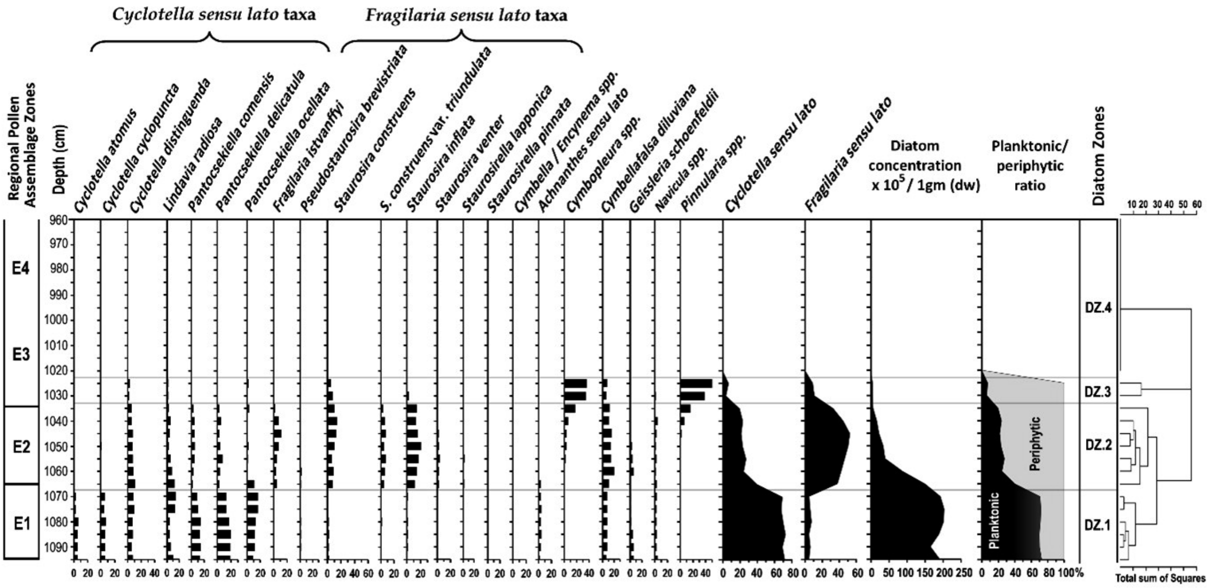
Based on changes in the relative abundance of dominant taxa and the constrained cluster analysis, the following four diatom assemblage zones (DZ.1–4) were recognized:

Stable isotopes

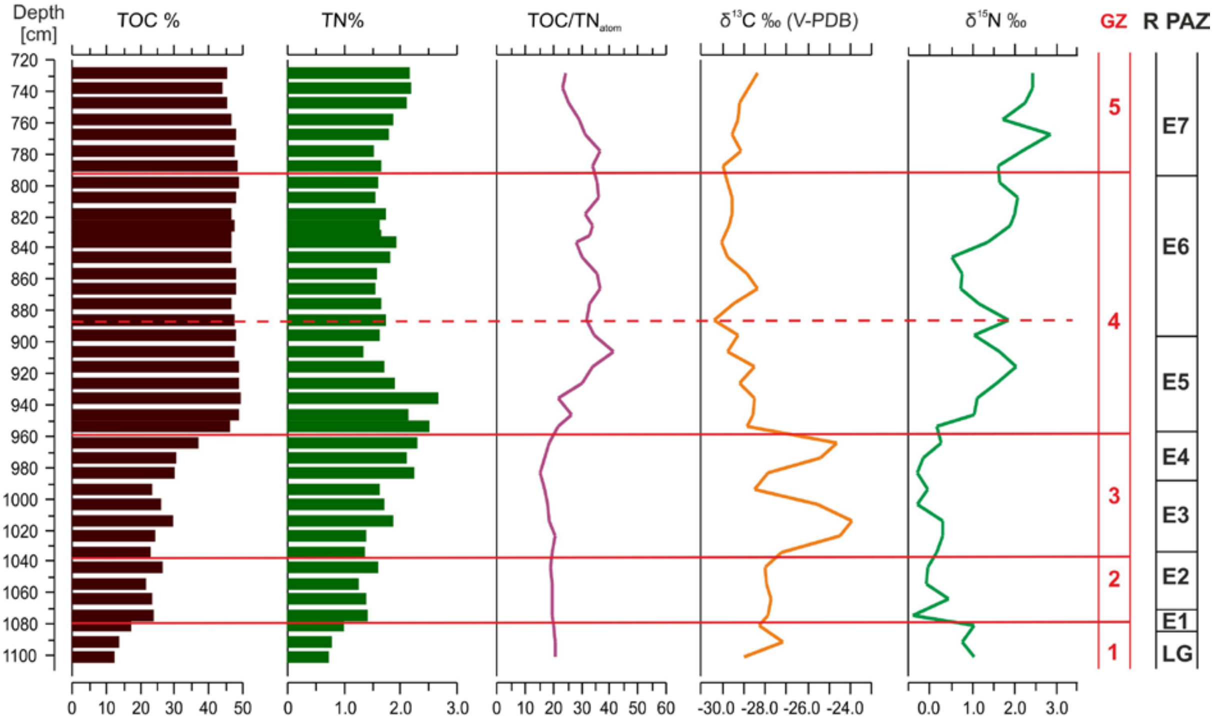
In the studied sediments, the amount of total organic carbon (TOC) rises from 12.5 to 48.6% and total nitrogen (TN) from 0.7 to 2.7% (Text-fig. 8). The TOC/TN$_{atomic}$ ratio fluctuates from 16 to 42. The carbon isotope ratio varies between -30.4 and -23.9‰, while the nitrogen isotope ratio varies between -0.4 and 2.9‰ (Text-fig. 8).

The organic and mineral matter content

Significant variations in the proportions of organic matter (LOI 550) and mineral matter were noted in the core (Text-fig. 9). Two phases are clearly distinguishable. The first is characterised by a significant share of mineral matter, fluctuating at around 50%. This stage is associated with lake sedimentation and covers a section of the core from a depth of

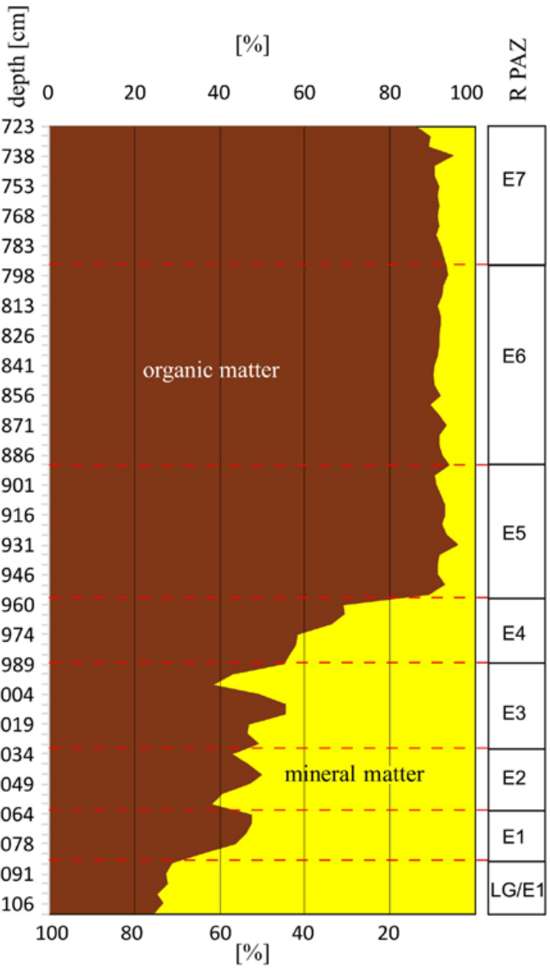


Text-fig. 7. Percentage diatom diagram of the Ża-19 profile with diatom valve concentration, planktonic and periphytic ratio and the diatom zones based on the cluster analysis.



Text-fig. 8. Diagram of the results of isotopic analyses of sediments from the Ża-19 core against the division into RPAZs.

1100 to 960 cm. It includes the palynostratigraphic zones LG/E1, E1, E2, E3, E4. The second stage, associated with peat sedimentation, is characterised by a significant proportion of organic matter of around 80–90%. This stage includes the palynostratigraphic zones E5, E6 and E7.



Text-fig. 9. Percentage share of mineral and organic matter in the Ża-19 core.

PALAEOHYDROLOGICAL CHANGES OF THE LAKE-BOG ECOSYSTEM IN ŻABIENIEC

The multi-proxy analyses carried out on biogenic sediments of the Żabieniec (Ża-19) core identified five basic phases in the development of the lake-bog ecosystem.

Phase 1 – Initial stage of the lake (transition from the Late Saalian into the Eemian Interglacial E1 RPAZ).

At that time the palaeolake was formed, probably as a result of melting dead ice blocks (morainic till in the bedrock; Text-fig. 2). The water body in Żabieniec was a relatively shallow lake, but with a zone of open water, as indicated by the results of fossil assemblages of diatoms, Cladocera and other organisms in the Ża-19 profile. Algae and macrophyte communities (*Nymphaeaceae, Ceratophyllum*) also developed at this time, with ferns entering at the end of the phase; these were confirmed based on the number of sporangia present. *Glomus* sporangia were also identified, which in this case may indicate increased erosion from the catchment area (Gerdeman and Trappe 1974), as confirmed by the results of the mineral matter content (max 71%). These results also confirm the geochemical data analysis. A gradual increase in the share of TOC and TN was also noted in this phase, reflecting a greater content of organic matter in the sediments. A TOC/TN$_{atom}$ score around 20 indicates the presence of both primary (algae) and terrestrial organic matter due to erosion from the catchment. The influx the material from the land may have been caused by higher water level and washout of the catchment.

Phase 1 is also associated with an already intensively developed diatom assemblage. The great abundance of well-preserved small planktonic *Cyclotella sensu lato* with a clear reduction in the abundance of fragilarioid taxa is indicative of continuing rising temperature (Rühland *et al.* 2015), associated with increasing water level and prolonged thermal stratification of a slightly alkaline, oligo- to mesotrophic open freshwater environment during a warm-humid climate (Pidek *et al.* 2021b; Zalat *et al.* 2021). In addition, the marked transition to planktonic dominance at the expense of small fragilarioid taxa serves as evidence of a rapid increase in lake level (Rühland *et al.* 2015; Zalat *et al.* 2018). This diatom zone is correlated well with the regional pollen zone (RPAZ) E1; it suggests that the beginning of the Early Eemian is characterized by improved climatic conditions and supports existing evidence for climatic warming.

The results of the climatic reconstruction indicate a gradual increase in total precipitation (over 450 mm) accompanied by an increase in temperature. The mean annual temperature still fluctuates around 0ºC, with two distinct episodes of growth. The mean temperature in January increases dynamically (from -15ºC to -8ºC), but remains at a few degrees C in July (Pidek *et al.* 2022); the largest changes were recorded at the beginning of phase 1 of the development of the lake.

Phase 2 – Stabilization of the conditions of the lake ecosystem (E2 RPAZ and the older part of the E3 RPAZ of the Eemian Interglacial).

The best proof that conditions stabilized lies in the nature of the Cladocera assemblages. In this phase, even species richness was observed, with a high and stable total number of Cladocera individuals (from 31 550 to 50 300 spec./cm^3). The share of planktonic species reaches a maximum of 46% and decreases at the end of the phase. Algae are beginning to develop intensively. In this phase, they reach their maximum number (max 50 000 pcs./cm^3) and the continuous growth of macrophytes is recorded. The number of fern sporangia also increases, indicating that the coastal zone of the lake is overgrown. *Rotifera* eggs appear in this phase and *Turbellaria* cocoons are constantly present. These findings seem to confirm the existence of stable environmental conditions in the lake.

The number of diatoms decreases significantly and they disappear at the end of the phase. A marked change in the environment occurs after the earliest part of the Eemian warming (E1 of the previous zone). The diatom composition indicates a clear decline in the abundance of the warmth-loving small planktonic *Cyclotella sensu lato* species and an increase in alkaliphilous benthic cold-loving fragilarioid taxa, with the significant occurrence of the epiphytic *Cymbellafalsa diluviana* (Zalat *et al.* 2022). The identified diatom assemblage signifies a prominently shallow, alkaline, mesotrophic freshwater environment associated with a lowering water level. However, this is not in line with the conclusions based on the results of other proxies.

Following this, the share of organic matter, mainly of primary origin, increases. At a depth of 1020 cm, very high δ13C values can be seen; this may indicate the presence of matter supplied from land as a result of the washing of material eroded from the catchment, or due to flooding of the coastal peatlands as a result of rising water levels. The TOC/TNatom and δ^{13}C are invariable and confirm the stable conditions.

Phase 2 of the development of the lake is correlated with a gradual increase in precipitation (up to 700 mm). Mean temperatures also increase. The highest increase in temperature is recorded at the end of phase 2 of the development of the ecosystem. The mean annual temperature increases from 0ºC to approx. 10ºC. The mean January temperature increases from (-13ºC) to about (-5ºC). The mean July temperature has the smallest amplitude, and reaches about 20ºC at the end of the phase (Pidek *et al.* 2022).

Phase 3 – Decline of the lake ecosystem (E3 and E4 RPAZs of the Eemian Interglacial).

As this stage ends with the transformation of the lake, it is arguably a key developmental stage, during which the nature of the ecosystem changes dramatically. The lake in Żabieniec underwent paludification relatively early, in the E5RPAZ, and since then, until the end of the interglacial, it functioned as a peat bog.

This is evidenced by a number of biological and geochemical indicators. In this phase, the number of Cladocera remains decreases significantly (from 55 050 ind./cm^3 to 10 250 ind./cm^3), but the number of taxa increases (max. 18). This can be attributed to the gradual decrease of open-water species and their later disappearance, e.g. *Bosmina longirostris*, and this coincides with the appearance of other species associated with peat bog ecosystems. At the onset of the phase, the share of *B. longirostris* is relatively high, which would suggest a slight increase in water levels. This stage also demonstrates very intensive development of macrophyte assemblages, represented by the presence of maxima of *Ceratophyllum* hairs and *Nymphaeaceae* trichosclereids. This may suggest a decrease in water levels or an increase in water productivity (Kowalewski 2014), indicated by a decrease in the proportion of *Bosmina longirostris* (Błędzki and Rybak 2016). *Stratiotes aloides* spikes appear occasionally, confirming its presence as a plant in the macrophyte zone of the overgrowing lake (Kowalewski 2014). This suggests the dynamic overgrowth of the lake, which may lead to oxygen depletion and, consequently, the occurrence of oxygen deficits; this seems to confirm the presence of *L. acanthocercoides*: a cladoceran species that can live in such conditions (Fryer 1968; Szeroczyńska 1998). This stage, characterised by possible oxygen deficits, is followed by a rise in *Chironomidae* assemblages identified on the basis of head capsules. *Turbellaria* cocoons are also identified, which increase significantly towards the end of the phase.

Following this, the diatom assemblages disappear, coinciding with the Eemian climatic optimum. The low abundance of diatoms may be attributed to unfavourable conditions in the paleolake, associated with a distinct lowering in water level during the period of deposition, or their dissolution due to greater alkalinity associated with climate warming.

The share of organic matter increases significantly at the expense of mineral matter. This indicates the development of vegetation in the water body and in the catchment area. In this phase, two peaks of very high δ13C values may indicate the presence of terrestrial organic matter in the sediments (Mirosław-Grabowska and Gąsiorowski, 2010. The supply of deposits from the land could derive from washings of material eroded from the catchment, or the flooding of the coastal peatlands as a result of rising water levels. In addition, high carbon isotope values reflect the possibility of reducing conditions with an oxygen deficit suggested by the Cladocera data (presence *L. acanthocercoides*) (Fryer 1968; Szeroczyńska 1998).

The overgrowth of the lake and its consequent paludification took place in a warm and humid climate. This phase was accompanied by a continuous increase in total precipitation, reaching a maximum at its end. At that time, the total precipitation amounted to 1200 mm. The beginning of the phase was associated with a rise in temperature, which remained high and then began to fall towards the end of the phase. The mean annual temperature increased from approx. 8ºC to around 12 ºC, and then dropped to approx. 10ºC. The mean temperature in January fluctuated a little above 0ºC. The highest temperature amplitudes were recorded in July; the optimum was recorded during this phase, increasing to over 20ºC and then dropping to a dozen or so degrees (Pidek *et al*. 2022).

Phase 4 – Transformation and development of the peatbog ecosystem (E5 and the beginning of the E6 RPAZ).

At this point, the planktonic species of Cladocera (*B. longirostris*) is gradually disappearing from the ecosystem, indicating that the lake has become overgrown and paludified (Text-fig. 10). This process was identified at the transition of phases 3 and 4, i.e. with transformation ending phase 3 and beginning phase 4. The development of the bog is confirmed by the intensively increasing share of the Cladocera bog species: *A. excisa, K. latissima,* and *O. tenuicaudis* (Błędzki and Rybak 2016). In this phase, the share of species richness and the total number of Cladocera decreases significantly. A significant decrease in the water level and a change in the nature of the ecosystem are also very well confirmed by the results of the NPP analyses. In this phase, the share of *Pediastrum* occurring in water reservoirs disappears. At the beginning of the designated phase, the macrophytes *Ceratophyllum, Nymphaeaceae* and *Stratiotes aloides* also disappear. At the same time, swamp plants such as ferns develop, identified on the basis of counted spores. Animals also grow in number: the number of *Chironomidae, Rotifera*, and *Turbellaria* increases, with their cocoons being identified in all samples of the phase.

At the beginning of the E4 RPAZ and E5 RPAZ palynostratigraphic phases, *Oribatida* carapaces appear incidentally (in two samples), which confirms the existence of the peatbog ecosystem (Lehmitz 2014). Phase 4 of the ecosystem development is also associated with the intensive development of fungi, identified by the presence of spores from *Glomus, Microthyriaceae* and *Alternaria* spp. These organisms successively increase their numbers during the designated phase 4; this is most likely related to their development on decaying plant remains (Hai *et al*. 2011). The geochemical analyses indicate that the sediment has a highly organic nature, with the share of organic matter fluctuating around 90%. The high TOC/TN ratio confirms the terrestrial origin of the matter. This is most likely associated with the existence of a raised bog. These results also seem to indicate the cessation of erosion processes in the catchment area, which was caused by the dense vegetation cover of the catchment area.

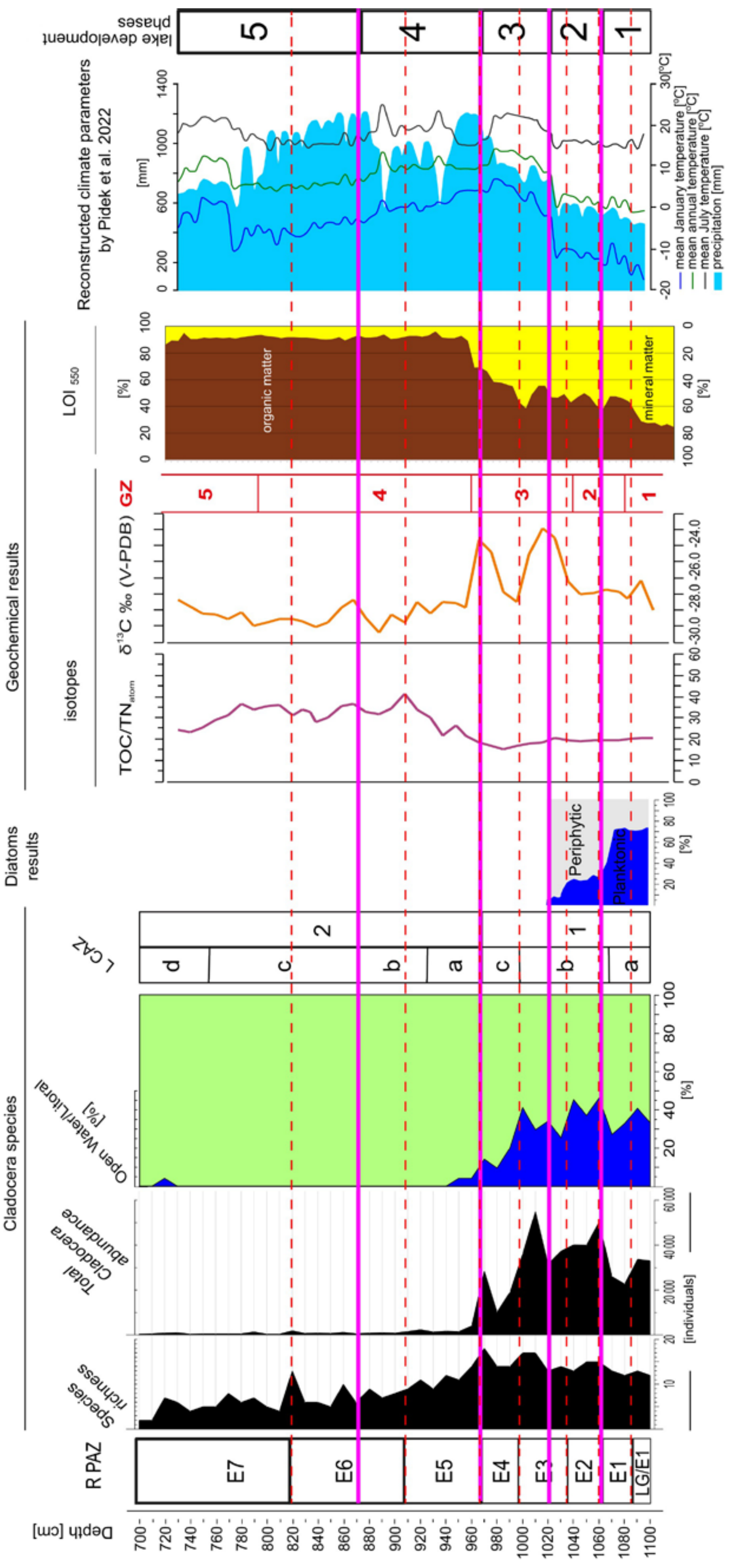
Phase 4 of ecosystem development is correlated with the climatic optimum. This period appears to be characterized by high temperatures. The mean annual temperature is around 10ºC, the mean January temperature is around 0ºC. The highest amplitudes were reconstructed for the mean July temperature: the value fluctuated around 20ºC, but clear decreases (up to 15 ºC) and increases (up to 25 ºC) are visible. Precipitation during this phase was relatively high. The beginning and the end of the phase are correlated with the mean precipitation sums of 1100 mm. In the middle part of the phase, there are visible drops in the sum of precipitation, even to about 500 mm (Pidek *et al*. 2022).

Phase 5 – Stable conditions of the peatbog ecosystem (E6 and E7 RPAZ)

This phase of the development of the lake-bog ecosystem is associated with the reign of stable environmental conditions in the bog, and thus the end of the interglacial. There are littoral species of Cladocera, with a significant predominance of *Ch. sphaericus* and a group of small Alonas. The share of *A. excisa* is also significant, which may indicate a low pH in the waters circulating in the fen (Błędzki and Rybak 2016).

In the initial stage of the phase, ferns occur; however, their number decreases and they disappear completely at the end of the E6 RPAZ. The beginning of the phase is associated with the collapse of the fauna, with gaps in the population of *Chironomidae* and *Rotifera*. These organisms appear again at the end of the phase. *Turbellaria* cocoons occur continuously, and their numbers peak in this level. This phase is also associated with a decline in the number of fungal spores: *Glomus, Microthyriaceae* and *Alternaria spp.* At the end of the phase, a renewal can be seen, identified by an increase in the number of spores. Geochemical analyses indicate a constant and very high share of organic matter, fluctuating around 90% (Text-fig. 9).

The end of the interglacial is associated with high precipitation totals at the beginning, reaching 1100



Text-fig. 10. Lake development phases of the Ża-19 core. From left to right, RPAZs, Cladocera species richness, Total Cladocera abundance, P/L ratio and L CAZs, periphytic *vs.* planktonic diatom species, geochemical results and zonation, percentages of organic matter and climate reconstruction parameters acc. to Pidek *et al.* (2022).

Zone/ subzone	Depth [cm]	Description
GZ1	below 1080	The lowest sediments (i.e. from a depth of 1080 cm) are characterized by the lowest concentration of organic carbon, i.e. ca. 14%, as well as by nitrogen below 0.1% (Text-fig. 8). The TOC/TN$_{atomic}$ ratio remains at an even level of 20. In the lowest sample of organic sediments, the $\delta^{13}C$ values vary between -29 and -27.1‰ (Text-fig. 8). The $\delta^{15}N$ values are about 1‰ (Text-fig. 8).
GZ2	1080–1040	In this part of the profile, the concentrations of organic carbon and nitrogen increase to ca. 24% and 1.4%, respectively. The TOC/TN$_{atomic}$ ratio is at the same level of 20. Initially, the $\delta^{13}C$ values are similar to those of the underlying deposits (ca. -28‰) and then quickly increase to -24.5‰. The $\delta^{15}N$ values initially drop to a minimum value of -0.4‰, and then rise to 0.3‰.
GZ3	1040–960	The concentration of organic matter rises, TOC values increase to ca. 37%, and TN values to 2.3%. The TOC/TN$_{atomic}$ ratio drops to 16–17. The carbon isotopic values reach their maximal value twice: up to -23.9 and -24.6‰. The $\delta^{15}N$ values initially decrease to -0.3‰, then increase to 0.3‰.
GZ4	960–790	The amount of organic carbon increases to 46% and then remains constant at ca. 47–48%. The nitrogen concentration initially rises to a maximal value of 2.7% (depth of 930 cm), and then drops to 1.5–1.7%. The TOC/TN$_{atomic}$ ratio irregularly increases to 42, and then fluctuates between 28 and 37. The $\delta^{13}C$ values firstly decrease to -30.4‰, rise to -28.3‰ and vary around -29‰. The $\delta^{15}N$ values initially increase to 2.1‰, then drop to 0.5‰ and rise again to ca. 1.7–2‰.
GZ5	above 790	The TOC values slightly decrease to ca. 45%, and the TN values increase to 2.2%. The TOC/TN$_{atomic}$ ratio drops to 24. The carbon isotope values slightly increase to -28.3‰. Finally, the $\delta^{15}N$ values rise to 2.4‰.

Table 5. Characteristics of the geochemical zones distinguished in the Ża-19 profile.

mm, and then a decrease in the precipitation totals to about 700 mm (Pidek *et al.* 2022). At the same time, the continentalism of the climate is increasing; although the temperatures remain high during the summer period, the mean annual temperature drops significantly, due to a rapid decrease in temperature during the winter months.

DISCUSSION

The Eemian lakes examined in the present study were first discovered during the re-survey of the Detailed Geological Map of Poland (sheet Garwolin No. 599). Following their discovery, the sites were subjected to detailed palaeogeographical research, particularly regarding their palaeoclimatic, palaeoecological and palaeohydrological aspects. The research to date has revealed the various stages of development of the Eemian lakes.

The multi-proxy palaeolimnological analyses carried out on the biogenic sediments of the Żabieniec site indicate that the origins of the lake lie at the end of the Saalian Glaciation. This would have been around the same time as is recorded in the sediments of other Eemian lakes in the Garwolin Plain (Kozłów (Suchora *et al.* 2022), Struga (Bober *et al.* 2018; Zalat *et al.* 2021), Puznówka (Kultys *et al.* 2022), Jagodne (Bober *et al.* 2021), Niesadna (Bober 2022, mnsc). Similarly, sediments of the Late Saalian Glaciation were also recorded at several other sites in central Poland, and it has been suggested that the lake shares a similar origin to that in Puznówka, i.e. caused by the melting of a block of dead ice buried in Late Saalian till (Kultys *et al.* 2022). This is the typical situation for areas with fresh post-glacial relief, characterised by numerous melt depressions successively filled with sediments during the Eemian Interglacial and Vistulian (Roman *et al.* 2021).

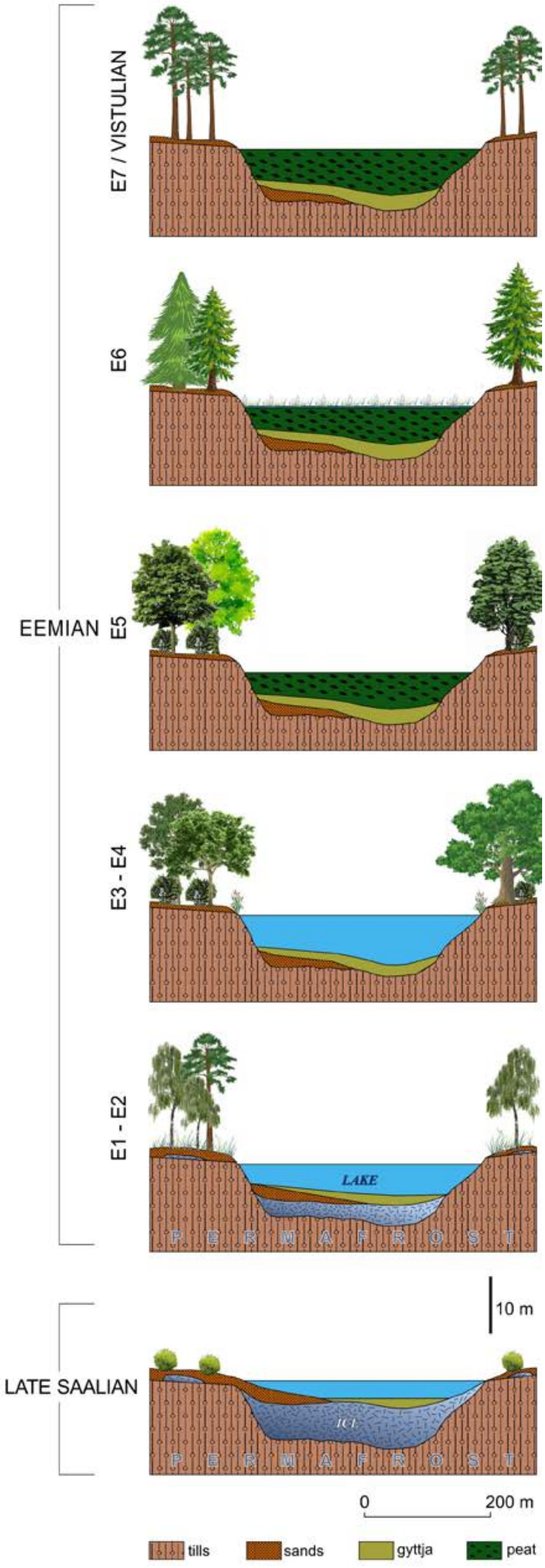
Most of the data on the nature of the lake was obtained by analysis of Cladocera and diatoms from the Ża-19 core. The findings indicate that it was relatively shallow, initially oligotrophic, and then gradually meso- and eutrophic, which is further supported by the stable isotope analyses. In addition, the results of phyto- and zooplankton and isotope analyses are in line with the data obtained from the plant macroremains (Ża-0 core). Strong eutrophication is clearly visible even in the E4 RPAZ hazel phase, during which the water body begins to shallow. This was undoubtedly influenced by the local conditions in the catchment area and the lake basin. Similar changes in water trophicity and palaeolake evolution have been reconstructed for the sites: Besiekierz (Mirosław-Grabowska and Niska 2005), Kaliska (Mirosław-Grabowska and Niska (2007), Imbramowice (Mirosław-Grabowska and Gąsiorowski 2010), Ławy (Hrynowiecka *et al.* 2018). The hazel phase (E4) was associated with the intensive development of macrophytes and the rapid growth of biogenic sediments. Palaeobotanical analyses indicate the overgrowth of the lake with associations of *Ceratophyllum* and *Nymphaeaceae*, with an admixture of *Stratiotes aloides*.

From the early stages of the E5 RPAZ, the longest phase of the Eemian interglacial, lasting about 7,300 years (Lauterbach *et al*. 2012), the lake began to undergo transformation processes and turned into a peat bog. Peat accumulation also continued in the telocratic period of the interglacial and the early Vistulian.

Taking the results of all analyses together, compiled in a synthetic form in Text-fig. 11, it can be seen that the record in the hornbeam phase is incomplete, with the younger part of this phase being absent. The biogenic sediments of the lake in Żabieniec (Ża-19 core) turned out to be a valuable source of data about the palaeohydrology of the Eemian lakes. Any sedimentary breaks (Hrynowiecka *et al*. submitted) that appeared at the transition of the hornbeam phase into the spruce-fir phase were detected by the use of subzonation by Kupryjanowicz and Granoszewski (2018). Although this division lacks absolute dating, it is possible to distinguish synchronic periods. The situation of the sedimentary breaks, and their possible causes in the Eemian hornbeam phase, were analysed in detail based on palynological data from Northern Podlasie (Kupryjanowicz 2008), which includes a hiatus in the sediments covering the younger part of the hornbeam phase, and sometimes also the spruce-fir phase. The author attributes this break to *inter alia* lowering of the erosional base that caused drying of the lake and the lack of possibility of deposition of organic deposits. Presumably, the water level in the Eemian lakes of Northern Podlasie also dropped significantly.

Other adjacent water bodies in the same region did not shallow as quickly, and continued to function as lakes throughout the interglacial period. One example of such a lake is Kozłów, which is about 6 km from Żabieniec in a straight line (Suchora *et al*. 2022). Kupryjanowicz (2008) proposes that the lowering of the water level in the Eemian lakes in the hornbeam phase was preceded by a high water level. Traces of this phenomenon can be found in the profiles of Struga (Zalat *et al*. 2021) and Parysów, in the form of a visible increase in the number of littoral species (Bober 2022, mnsc).

Previous studies from Poland also suggest drainage in the hornbeam phase, e.g. Główczyn (Niklewski 1968), Besiekierz (Janczyk-Kopikowa 1991), Bieganin (Malkiewicz 2003). Various changes, such as a decrease in the sedimentation rate, are also visible in Eemian sediments from the following sites: Switzerland (Borówko-Dłużakowa and Halicki 1957), Dziewule (Binka and Nitychoruk 2001), Kontrowers (Kupryjanowicz *et al*. 2003), Ustków (Kołaczek *et al*. 2016). However, as these studies tend to have quite low resolution, no detailed examination of this problem is possible.



Text-fig. 11. Main phases of the development of the Żabieniec palaeolake against the background of the Eemian RPAZs.

Thus, the Żabieniec site joins the list of Eemian paleolakes characterized by disturbances in the hornbeam phase, probably even at the early stage of this long phase. These appear to be caused by the convergence of the local geological and geomorphological situations, i.e. the presence of a shallow and extensive lake basin, with the prevalent climatic factors; one such factor is climate continentalization, manifested by a progressive decrease in the temperature of the coldest month, a decrease in the annual temperature and decrease in annual rainfall.

Other similar water bodies, with an early stage of paludification, were also observed at Jagodne (Bober *et al*. 2021) and Parysów (Bober 2021). Moreover, the Eemian deposits from the Słup site present no record of the entire E5 and E6 phases of the RPAZ (Kultys *et al*. 2023). The profile from the paleolake in Słup was collected in the lake shore zone, where the periods of shallowing and water level rise are best recorded.

Previous studies seem to indicate the presence of two types of Eemian palaeolake evolution in such a small area. While those in the shallow basins paludified and were not functioning in the end of the Eemian optimum, other lakes continued to function until the final phase of the Eemian interglacial, as observed in Kozłów (Suchora *et al*. 2022) and Struga (Bober *et al*. 2018; Zalat *et al*. 2021).

Many palaeoecological studies indicate the highest water level to be present in the hazel phase (E4 RPAZ) (Mirosław-Grabowska *et al*. 2018, Roman *et al*. 2021). This period was characterised by very favourable climatic conditions, characterized by high precipitation and relatively high temperatures. The high humidity and maritime nature of the climate are clearly related to the transgression of the Eemian Sea, whose sediments were found by Makowska (1979, 2009) in the Lower Vistula Valley. Mojski (1993) stressed that there are also older marine deposits of the Sztum Sea that preceded the palaeobotanically dated Eemian. However, the proper marine transgression started in the E3 *Quercus–Ulmus* phase (acc. to Zagwijn 1989) and culminated during the E4 (*Corylus* phase). These conclusions are in line with the observations by Roman *et al*. (2021) that some of the Eemian lakes in Central Poland exhibited a high water level as early as the E3 RPAZ and continued during the E4 RPAZ. In the Garwolin Plain, the presence of high lake levels in the E4 RPAZ has been confirmed by palaeoecological analyses carried out on lake sediments in Kozłów (Suchora *et al.* 2022), Struga (Bober *et al*. 2018; Zalat *et al*. 2021) and in Słup (Kultys *et al*. 2023). During this period, however, the lake in Żabieniec was heavily overgrown. At the end of the E4 zone, it transformed and functioned as a peat bog until the end of the Eemian interglacial. Undoubtedly, this state and character of the lake observed during high rainfall events was influenced by local conditions in the lake basin. This is a relatively early transformation of the lake into a peat bog, as such a process occurred later in other lakes in northern Poland. An example is the palaeolake Starowlany (Niska and Kołodziej, 2015) Such variation in the functioning of lakes within such a small area clearly highlights the significance of the role played by local factors in shaping their development.

CONCLUSIONS

Due to its long pollen succession record, now supplemented by Cladocera, diatom and isotope analyses, the Żabieniec palaeolake is one of the key sites of the Eemian Interglacial in Central Poland. Its sediments have allowed a detailed reconstruction of the evolution of the paleolake under changing climate conditions and other environmental factors.

The palaeolake in Żabieniec was a shallow water body whose trophy level ranged from low, i.e. mesotrophy, to moderate, i.e. eutrophy, and was most likely formed by the melting of a block of dead ice.

- The study relates Local Pollen Assemblage Zones (LPAZs), Cladocera Assemblage Zones (CAZ) and diatom phases (DAZ), as well as isotope zonation, to the Regional Pollen Assemblage Zones E1–E7 (RPAZs) widely used for correlation of vegetation and climate changes during the Eemian.
- The pollen record also enabled subzonation of the main RPAZs according to the new division of the Eemian by Kupryjanowicz and Granoszewski (2018). In addition, the detailed Cladocera and diatom record, and the changing composition of isotopes, enabled the identification of changes in trophy, depth and aquatic vegetation and allowed conclusions to be drawn regarding climate and water-level changes.
- The beginning of the water body dates back to the Late Saalian/Early Eemian transition, characterized by low total abundance, low Cladocera species richness and small numbers of diatom remains.
- The E1–E3a RPAZs period is indicative of dynamic changes in the early stages of lake functioning, which correspond to the development of vegetation from birch communities to riverine forests with elm and oak.
- The exceptionally rich Cladocera and diatom assemblages complement the NPPs data and agree

with pollen-based climate reconstructions. They reflect relatively stable conditions during the E3a–E5a RPAZs and gradual lake shallowing, starting from the end of E4 RPAZ. At that time a strongly stratified water column with anoxic bottom waters probably occurred.

- The characteristic feature of the Żabieniec site is its quick paludification and the fact that peat accumulation only began in the early E5 RPAZ. This period is characterized by a significant decrease in water level that started the gradual ecological transition.
- The Late Eemian (E6–E7 RPAZs) is characterized by the introduction of coniferous forests as a result of cooling, and is marked by a higher water level, as indicated by higher percentages of *Pediastrum* and *Botryococcus* algae.

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