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Chironomidae-inferred anthropogenic and natural processes in moat and palaeochannel systems
– Rozprza case study

Chironomidae w badaniach antropogenicznych
i naturalnych procesów zachodzących w systemach
fos i paleokoryt – studium przypadku w Rozprzy

PhD thesis

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In Chapter III ("Chironomidae assemblage sequence in the Holocene deposits of the Luciąża River palaeomeander") unpublished results are presented.

Abstract

The aim of the study is a palaeoecological reconstruction of the environment in the area of the archaeological site in Rozprza on the Piotrków Plain (Łódź Voivodeship), including the history of transformations of local ecosystems. It focuses on the natural and anthropogenic processes taking place in them, as well as climate changes in the region. The basis of this study are the results of the analysis of subfossil Chironomidae assemblages from five sediment profiles from the moat system and palaeo-oxbow.

The changes in Chironomidae assemblages in the Late Glacial were investigated with the use of a lake profile taken from the palaeomeander (palaeo-oxbow) of the Luciąża River. The aim of the research was to reconstruct the mean summer air temperatures and hydrological changes in the period of Allerød and Younger Dryas (approx. 13.300 – 12.200 cal. BP). The obtained results constitute the well-documented report of the cool inter-Allerød oscillation ("Gerzensee Oscillation'') in East-Central Europe. Moreover, they reveal relatively high summer temperatures (up to 16˚C) in the Younger Dryas, which may indicate warmer local conditions at the end of the Vistulan or a high degree of continentalism during this stadial in central Poland.

Based on the Chironomidae assemblages, habitat changes in two types of water bodies were also reconstructed: the natural palaeo-oxbow and the moat from the late-medieval motte-and-bailey complex. The obtained results provided data for the reconstruction of the history of settlement in Rozprza and the functioning of the moat, including changes in the water trophic state. The research enabled tracking human influence on the moat ecosystem in the late medieval period and indicated the possible interference of the stronghold inhabitants in its flushing.

The record of Chironomidae, along with sedimentological and geochemical data from four cores of organic sediments collected at different points in the moat system, allowed the spatio-temporal characterisation of habitat changes. This resulted in mapping the habitats present in the moat during its functioning. The study has proven that even in a body as small and shallow as a moat, the pace and extent of ecological processes and associated habitats were not uniform. The differentiation of the moat habitats depended mainly on the depth of the bottom, exposure to denudation processes and fresh water supply from a nearby river.

The thesis also presents the results of an analysis of the morphological and trophic groups of Chironomidae, which is the first stage of research on the use of functional traits of these insects in palaeoecology. Sixteen types of Chironomidae larvae head capsules have been identified. It has been shown that the morphology of their mouthparts can serve as an indicator of habitat

changes, including physicochemical conditions and vegetation, to a similar extent as trophic guilds.

The obtained results confirm the great importance of Chironomidae larvae in palaeoecological and archaeological research. The results of the Chironomidae analyses have led to a better understanding of the ecology of artificial water bodies, such as medieval moats, and a comparison of the extent and rate of processes occurring in natural water bodies and man-made reservoirs. They indicated that paludification happened much faster in the artificial water body (moat) than in the oxbow lake. In natural reservoirs, Chironomidae communities were mainly shaped by global and regional climatic changes, while in the moat the determinants of the occurrence and composition of Chironomidae were local habitat changes.

Streszczenie

Celem pracy jest paleoekologiczna rekonstrukcja środowiska w rejonie stanowiska archeologicznego w Rozprzy na Równinie Piotrkowskiej (woj. łódzkie), w tym określenie historii przekształceń lokalnych ekosystemów. Praca skupia się na naturalnych i antropogenicznych procesach w nich zachodzących, a także zmianach klimatu w regionie. Podstawą opracowania są wyniki analizy subfosylnych zgrupowań Chironomidae z pięciu profili osadów z systemu fos i paleostarorzecza.

Zmienność zgrupowań Chironomidae w późnym glacjale została zbadana z wykorzystaniem profilu jeziornego pobranego z paleomeandru (paleostarorzecza) rzeki Luciąży. Badania miały na celu odtworzenie średnich temperatur lata i zmian hydrologicznych w okresie allerødu i młodszego dryasu (ok. 13 300 – 12 200 lat cal. BP). Uzyskane wyniki stanowią jedno z pierwszych, dobrze udokumentowanych stwierdzeń chłodnej oscylacji interallerødzkiej (tzw. „Gerzensee Oscillation”) w Europie Środkowo-Wschodniej. Wskazują ponadto na stosunkowo wysokie temperatury lata (do 16˚C) w młodszym dryasie. Może to wynikać z lokalnie cieplejszych warunków pod koniec zlodowacenia wisły bądź wysokiego stopnia kontynentalizmu w tym stadiale w Polsce środkowej.

Na podstawie subfosylnych zgrupowań Chironomidae zrekonstruowano również zmiany siedliskowe w dwóch typach zbiorników wodnych: naturalnym paleostarorzeczu i fosie, wchodzącej w skład kompleksu późnośredniowiecznego gródka stożkowatego. Uzyskane wyniki dostarczyły danych do rekonstrukcji historii osadnictwa w Rozprzy i funkcjonowania fosy, w tym zmian stanu troficznego wody. Badania umożliwiły prześledzenie wpływu człowieka na ekosystem fosy w późnym średniowieczu i wskazały na prawdopodobną ingerencję mieszkańców gródka w jej przepłukiwanie.

Zapis występowania larw Chironomidae, wraz z danymi sedymentologicznymi i geochemicznymi z czterech rdzeni osadów organicznych pobranych w różnych punktach systemu fos, pozwolił na scharakteryzowanie zmian siedliskowych w czasie i przestrzeni. W konsekwencji dokonano mapowania siedlisk obecnych w fosie podczas jej funkcjonowania. Badania wykazały, że nawet w tak małym i płytkim zbiorniku wodnym jak fosa, tempo i zakres procesów ekologicznych oraz związanych z nimi siedlisk nie były równomierne. Zróżnicowanie fosy zależało głównie od głębokości dna, ekspozycji na procesy denudacyjne i zaopatrzenia w świeżą wodę z pobliskiej rzeki.

W pracy przedstawiono również wyniki analizy grup morfologicznych i troficznych Chironomidae, będącej pierwszym etapem badań nad wykorzystaniem cech funkcyjnych

(*functional traits*) tych owadów w paleoekologii. Udowodniono, że morfo-taksonomia na podstawie aparatu gębowego może być wykorzystywana do rekonstrukcji zmian siedliskowych, w tym warunków fizykochemicznych i roślinności, w podobnym stopniu, jak gildie troficzne.

Uzyskane wyniki potwierdzają duże znaczenie larw Chironomidae w badaniach z zakresu paleoekologii i archeologii środowiskowej. Wyniki analiz ochotkowatych umożliwiły poszerzenie wiedzy na temat ekologii sztucznych zbiorników wodnych, takich jak średniowieczne fosy, oraz porównanie zasięgu i tempa procesów zachodzących w zbiornikach naturalnych oraz stworzonych przez człowieka. Pozwoliły one wskazać na znacznie szybsze tempo paludyfikacji w zbiorniku sztucznym (fosa) niż w starorzeczu. W naturalnych zbiornikach zgrupowania Chironomidae były kształtowane głównie przez globalne i regionalne zmiany klimatyczne, podczas gdy w fosie determinantami występowania i składu Chironomidae były lokalne zmiany siedliskowe.

Chapter I. General introduction

Palaeoecology in climatic and environmental reconstructions

According to the most recent IPCC (Intergovernmental Panel on Climate Change) report, the global temperature rise is caused both by natural factors and cycles, and by human activity. The report draws the possible scenarios of global warming and points out the regional climate differences (IPCC, 2021). Facing this fact, societies, from common people to policymakers, are asking how the climate was changing in the past, what are the reasons, directions and implications of changes in the climate system both in regional and global scales. Although the first temperature measurements have been done in today's Poland as early as in the mid-17th century (Camuffo & Bertolin, 2012), the global temperature data time series have been recorded for no longer than since 1850 (Brohan *et al.*, 2006). Moreover, the historical measurements were not carried out evenly across the world (Menne *et al.*, 2018). To reconstruct the global climate in the long time scale, it is necessary to reach for information preserved in such palaeoarchives as ice sheets, terrestrial and marine sediments. The subfossil plant and animal remains preserved in sediments allow for reconstructions of habitats, ecosystems and landscapes. It is possible only with the assumption of the principle of uniformitarianism, which states that ''present is the key to the past'', and thus contemporary organism-environment relationships can be used as a model for past conditions (Scott, 1963; Rymer, 1978).

Pollen and plant macrofossils, diatoms, as well as stable isotopes and geochemical sediment composition are best known and most often used among the palaeoecological proxies. However, to achieve a reliable, holistic picture of the past environments, a wide spectrum of tools is necessary. Combined proxies can reveal the weaknesses and misinterpretations derived from a single analysis, as well as strengthen some other signals (Mann, 2002; Birks & Birks, 2006). One of the proxies commonly used in palaeolimnology are non-biting midge (Chironomidae) subfossils (Walker, 1995, 2001; Brooks, 2003).

Non-biting midges (Diptera Chironomidae)

Chironomidae is a taxonomically and ecologically diverse family of true flies (Diptera) from the suborder Nematocera. In total, ca. 7,000 chironomid species have been described so far (Pape *et al.*, 2011; GBIF, 2019), and this number is still growing. While only a couple of Western European countries have updated checklists (Rossaro *et al.*, 2019), the state of knowledge about the non-biting midge richness besides Holarctic region is far from being complete (Ferrington, 2008). Thus, even the assessment by Cranston (1995) that there are at least 10,000 chironomid species worldwide seems to be underestimated. Non-biting midges are not only species-rich, but also widespread and found across the world, including Antarctica (Ferrington, 2008). These holometabolous insects with flying, short-living adult stage, usually have four larval instars (Armitage *et al.*, 1995; Lackman & Butler, 2018). The larvae most often feed on periphytic algae or detritus, but there are many predators and filter feeders as well. Among phytophagous chironomids there are several mining species (Beiger, 2004). Others are associated with inundated wood (Armitage *et al.*, 1995; Courtney & Cranston, 2015). The larvae are common inhabitants of aquatic ecosystems, such as rivers, lakes, springs and streams. However, they are also often found in terrestrial and semi-terrestrial habitats (e.g. moist soil, bryophyte mats, lichen heaths) (Pinder, 1995; Delettre, 2000). Some species are known from extreme conditions, inhabiting e.g. saline waters, hot springs, phytotelmata, glaciers and even fresh dung (Cranston, 1995; Ferrington, 2008). The diverse ecological preferences of non-biting midges make them good indicators. They are used in the monitoring of water quality (Lindegaard, 1995; Woźniak *et al.*, 2018), but they can also indicate chemical pollution (Rosenberg, 1993; Lindegaard, 1995) and past environmental conditions (Walker, 2001; Porinchu & MacDonald, 2003; Brooks, 2006).

The sclerotised head capsules of larvae, on which the taxonomic identification is mostly based, are usually well preserved and abundant in the sediment deposits. As Chironomidae is a species-rich family, their subfossil assemblages are diverse and thus well representing environmental changes. The fast larval development, as well as a winged, mobile imago make them capable of almost immediate response to the change in local conditions. Most chironomid species have narrow ecological preferences, some of them are even stenotopic. The sensitivity of Chironomidae and their well-recognised autecology are excellent starting points for past environments reconstructions (Walker, 1995, 2001; Brooks *et al.*, 2007).

Chironomidae in palaeoenvironmental studies

The first studies concerning shifts in the non-biting midge assemblages in relation to the palaeoenvironmental changes were conducted in the first half of 20th century (Gams, 1927; Andersen, 1938; Deevey, 1942; Lastochkin, 1949). For next decades, however, chironomid analyses were rarely included in palaeoecological studies (Walker, 2001). The palaeolimnological studies involving chironomid history started to be conducted intensively in the 1980s. Their value as a proxy for tracking environmental changes increased after the introduction of the Chironomidae-based calibration data sets in the 1990s (Walker, 2001).

The application of quantitative reconstruction of past environmental variables was first presented by Imbrie and Kipp (1971). They used the transfer function approach based on foraminifera assemblages to reconstruct sea-surface temperature and salinity. The basic idea behind this method is to gain the ecological optima of taxa recorded as subfossils in the sediment deposits from the modern taxon data (training set). Training sets include the data derived from a wide range of surface sediment samples from the sites distributed along an environmental gradient to be reconstructed. After numerical modelling of the contemporary taxa responses to the measured environmental variables, the obtained calibration function can be used to transform the fossil biotic record into quantitative reconstruction of past temperature, water trophic state, salinity or other environmental variables (Juggins, 2009; Birks *et al.*, 2010). The introduction of the two-way weighted averaging method with the use of surface-sediment calibration data sets (ter Braak & van Dam, 1989) turned out to be crucial for the quantitative environmental reconstructions. The method has been adopted to the various biological proxies (Birks *et al.*, 2010; Juggins & Birks, 2012; Smol *et al.*, 2012).

The first calibration dataset based on chironomid assemblages was created by Walker (1991) for the palaeotemperature reconstruction in Atlantic Canada (Walker *et al.*, 1991). This proxy was considered '*the most promising biological transfer function approach for direct temperature reconstruction*' (Battarbee, 2000). Thus, a number of chironomid-based training sets have been created in many regions of the world. In Europe, chironomid-inferred climate reconstructions are possible with the application of several inference models (e.g. Lotter *et al.*, 1998; Larocque *et al.*, 2001; Luoto, 2009a; Heiri *et al.*, 2011; Self *et al.*, 2011; Luoto & Nevalainen, 2017; Luoto *et al.,* 2019; Kotrys *et al.*, 2020). Moreover, non-biting midge subfossils are also used for tracking changes in other environmental variables in regional and local scale (i.e. Luoto *et al.*, 2012). Nowadays, a number of chironomid-based calibration sets are available. Among reconstructed factors are: total phosphorus (Lotter *et al.*, 1998; Brooks *et al.*, 2001; Luoto, 2011), total nitrogen (Brodersen & Anderson, 2002), hypolimnetic oxygen (Quinlan & Smol, 2001; Luoto & Salonen, 2010), salinity (Eggermont *et al.*, 2006), chlorophyll a (Brodersen & Lindegaard, 1999; Langdon *et al.*, 2006), dissolved organic carbon (Larocque *et al.*, 2006), stream flow (Luoto, 2010), and water depth (Luoto, 2009b; Kurek & Cwynar, 2009).

Such a wide range of reconstructed variables may suggest that chironomids are not good indicators for none of them. In fact, they should not be used for reconstructing surrogate variables, or variables which have some indirect effect and are confounded with other factors, such as dissolved organic carbon (DOC) (Juggins, 2013). However, their usefulness as a reliable proxy for mean July air temperature in the Lateglacial and Holocene reconstruction is well proven (Walker, 2001; Brooks *et al.*, 2001, 2012). Besides that, there is a need to take into consideration the factors indirectly related to the air temperature, such as continentalism and insolation level

(Engels *et al.*, 2014; Nazarova *et al.*, 2017), as well as water trophic state. The latter is often considered as obscuring the climate reconstructions (e.g. Velle *et al.*, 2010), but Brooks *et al.* (2012) argue that such correlation is not universal, especially in warmer climates. Dickson and Walker (2015) referred to this debate, experimentally proving the direct linkage between midge emergence and survival, and air temperature. In fact, factors like trophic state, pH and salinity may be more significant at the local scale, while air temperature is rather a regional-level driver (Brooks *et al.*, 2001, 2007; Luoto *et al.*, 2012). Every reconstruction based on biological proxy, including chironomids, can be influenced by confounding factors (Heiri & Lotter, 2005; Velle *et al.*, 2010; Brooks *et al.*, 2012). Thus, the reconstruction results should be compared with independent climate proxies (e.g. pollen, stable isotopes) and the possible discrepancies should be carefully detected (Brooks *et al.*, 2012; Eggermont & Heiri, 2012).

First chironomid-temperature inference models were based on the water surface temperature data (e.g. Walker *et al.*, 2001). However, the surface water temperature might be highly variable and such data (taken from the exact point of the lake, at exact time) used for training set construction may lead to obscure or false results (Brooks, 2006). In fact, the relationship between air and surface water temperature is well proven (particularly in the temperate zone) (Livingstone & Lotter, 1998; Eggermont & Heiri, 2012; Luoto *et al.*, 2014). The air temperature greatly influences the distribution of the short-living winged adult stage (Brooks *et al.*, 2001; Płóciennik *et al.*, 2018), and nowadays the training sets are constructed using long-term climatic data from the meteorological stations (Brooks, 2006). The problem appears when there is an input of cold water from the glacier or snow bed to the lake, which lowers the chironomid-inferred air temperatures (Brooks *et al.*, 2001; Heiri & Lotter, 2010; Eggermont & Heiri, 2012). The training sets need to be calibrated considering such situations.

Chironomidae in environmental archaeology

Many palaeoecological studies are nowadays more and more often applied in environmental archaeology, to track changes in relations between past human societies and the environment (Dearing *et al.*, 2006). The most important palaeoecological proxies in archaeology (similarly as in palaeolimnology) seem to be pollen and plant macrofossils. Those methods have already been used in archaeology before World War II (Kozłowska, 1921; Jaroń, 1938, 1939; Moldenhawer, 1939). In comparison to beetles, which have a long history in archaeological studies (Whitehouse *et al.,* 2008; Elias, 2010), Chironomidae started to be applied in this kind of research relatively late. A pioneer archaeoentomological research in Poland, where chironomid analysis was applied, was undertaken by Czeczuga *et al.* (1979). However, it was the study by O'Brien *et al.* (2005), which turned out to be the crucial one, showing how much potential Chironomidae have in the archaeological studies on aquatic deposits (Ruiz *et al.* 2006).

Environmental archaeology is necessary in studying past settlement conditions, food economy and population movements. Some palaeoecological methods are undertaken during archaeological research of medieval defensive structures, such as moats (e.g. Beneš *et al.*, 2002; Kočár *et al.*, 2010; Brown & Pluskowski, 2011; Makohonienko, 2014; Koszałka, 2000, 2014). Although the sediment deposit of a moat is similar to that of small, natural water bodies (such as oxbows), no aquatic invertebrate analyses (neither Cladocera nor Chironomidae) have been implemented so far. The palaeolimnological research in Rozprza complements this gap, being considered one of the most comprehensive multi-proxy studies in Europe.

Rozprza archaeological site

Rozprza village is located in central Poland, in the Łódź region. The study site is situated in the middle section of the Luciąża River valley. Luciąża River is a tributary of Pilica River in the Vistula River basin (see Fig. 1, Chapter II).

Rozprza was considered one of the most important medieval strongholds in central Poland (Sikora, 2007, 2009). However, the results of the archaeological study conducted by Chmielowska in the 1960s indicated its extraordinarily small size and poor facilities (Chmielowska, 1966, 1982). In 2013-2015, Rozprza was included in the project of the non-destructive archaeological survey of the medieval strongholds of central Poland (Sikora *et al.*, 2015; Andrzejewski & Sikora, 2018). The multidisciplinary research revealed remnants of a settlement complex, including ramparts, moat system, channels and road, visible in the field. The large-scale geophysical and geochemical prospecting, aerial photography, as well as thorough geological mapping have shown a complex system of palaeomeanders and dikes in the vicinity of the archaeological site (Kittel *et al.*, 2015, 2018a,b; Sikora *et al.*, 2015). A thick (up to 2.5 m) layer of organic sediments and a number of well-preserved wood fragments and nuts suggested that with the application of a broad range of palaeoecological and palaeogeographical methods, the detailed evolution of the environment may be reconstructed. Such complex, extensive research including many methods of environmental archaeology were rarely conducted in central Poland (Kittel *et al.,* 2014). Therefore, Rozprza was chosen as the area for detailed multi-proxy study.

Material and methods

The sediments for palaeoecological analyses were collected from the walls of archaeological trenches. Three profiles of deposits – RP W1, RP W3(2), and RP W3(4) – were obtained from different parts of the main moat. The RP F2 core was taken from the thoroughly deepened and purified wall of the drainage ditch, which currently crosses the southern secondary moat. The RP W4 core of sediment was collected from the trench, located on the large palaeomeander approximately 100 m north-west of the stronghold (Fig. 1.1). The deposits were collected as monoliths using metal boxes with dimensions of 50×10×10 cm. This method enables preserving their undisturbed structure.

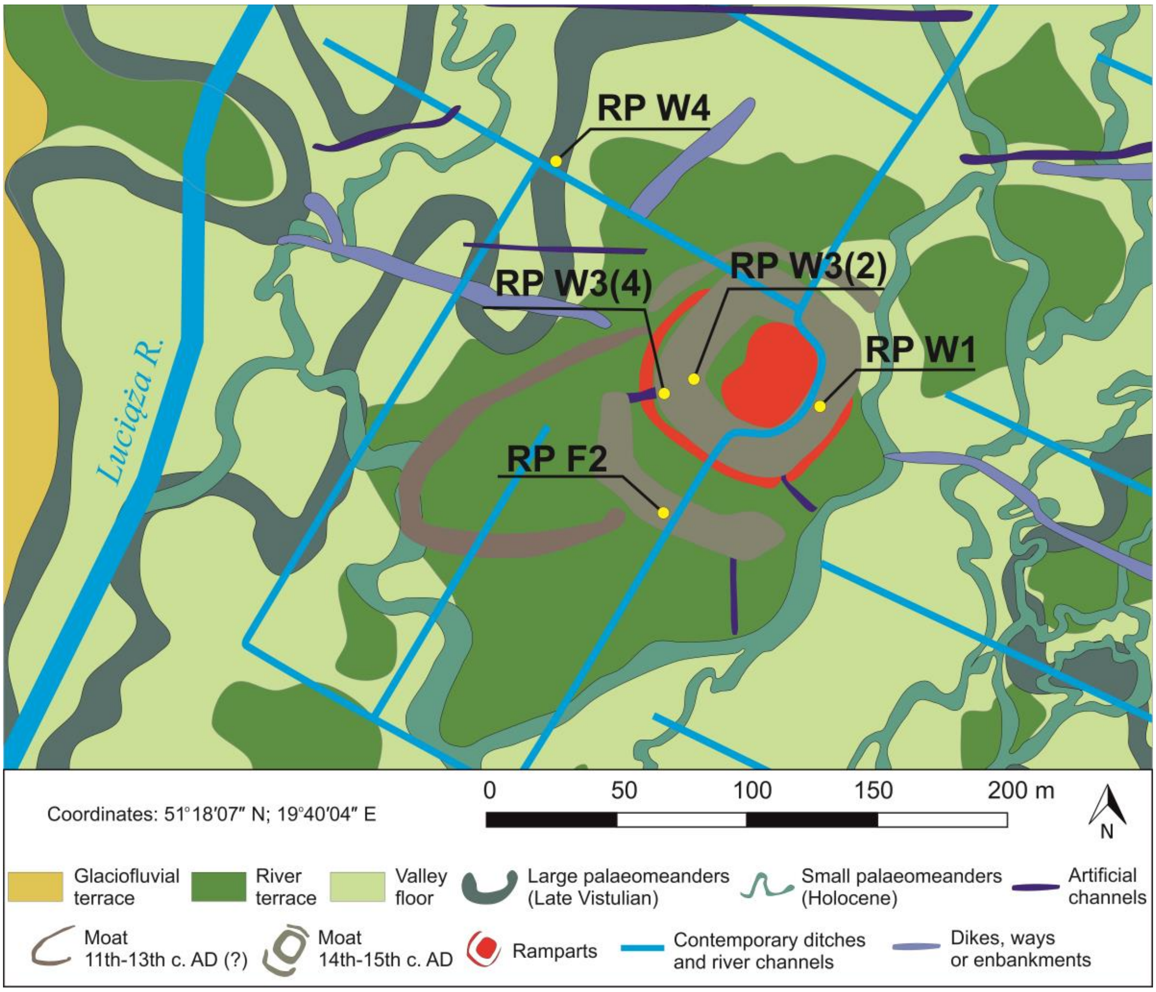

Fig. 1.1. The location of studied profiles in the vicinity of the Rozprza stronghold.

The sediment cores were transported to the laboratory. For Chironomidae analysis, the contiguous 2 cm slices of the sediment were taken from each profile, besides RP W3(2) core, from which they were collected with 4 cm resolution. In addition to Chironomidae, being the object of this dissertation, also pollen, plant macrofossils, diatoms, Cladocera, Coleoptera and geochemistry were studied.

Sample processing followed the standard method outlined in Brooks *et al.* (2007). Additionally, a kerosene flotation was used, following Rolland and Larocque (2007). The samples were wet-sieved in a 63 µm mesh with the use of a detergent in order to remove remains of kerosene. Sieved sediment was put into a Bogorov counting tray and scanned under stereo-binocular microscope. If possible, at least 100 chironomid head capsules from each sample were picked and mounted in Euparal® on microscope slides. Identification of chironomid head capsules to the highest possible taxonomic level was based mostly on Brooks *et al.* (2007), Andersen *et al.* (2013) and Schmid (1993). The publication by Bitušík & Hamerlík (2014) was used to identify some of the Tanypodinae head capsules. The identification of *Psectrocladius* (*Psectrocladius*) was based on the key by van Nieuwenhijzen (2017), whereas numerous subfossils of *Glyptotendipes caulicola* were identified on the basis of Contreras-Lichtenberg (2001). Nomenclature follows the above-mentioned literature. The ecological preferences of identified taxa were based on Brooks *et al.* (2007), Vallenduuk and Moller Pillot (2007), Moller Pillot (2009, 2013), Giłka (2011), Bitušík & Hamerlík (2014), and Vallenduuk (2017). Besides chironomids, head capsules of Simuliidae and Ceratopogonidae were also identified. Within biting midges (Ceratopogonidae), two morphotypes were recognised following Walker (2001). Black flies (Simuliidae) subfossils were not identified to the lower taxonomic level.

In total, the material obtained from the five studied profiles includes 7348 chironomid head capsules identified to 115 morphotypes (Table 1.1), as well as 130 Ceratopogonidae and 5 Simuliidae individuals. The material is deposited in the Laboratory of Palaeoecology and Archaeobotany (University of Gdansk).

Table 1.1. Summary of Chironomidae material collected within this study.

Profile	Location	Depth range (cm b.g.l.)	Number of samples	Samples volume range (cm^3)	Number of individuals	Number of morphotypes
RP W1	Main moat	0-50	23	16.5-56	935	59
RP W3(2)		28-136	27	5-70	2568	83
RP W3(4)		38-86	24	16-52	2219	63
RP F2	Second moat	20-70	25	13-44	116	18
RP W4	Palaeo-oxbow	20-214	63	1-36.5	1510	64

b.g.l. – below ground level

In order to obtain quantitative environmental reconstructions, the available training sets were used. The information about past climatic conditions in the Luciąża River valley was derived from Chironomidae data obtained from the palaeo-oxbow deposits (RP W4 profile, Chapter II). The mean July air temperature was reconstructed using East-European (Luoto *et al.*, 2019) and Swiss-Norwegian-Polish (Kotrys *et al.*, 2020) training sets.

The East-European training set (EE TS) is based on the 2-component WA-PLS (Weighted Averaging Partial Least Squares) regression model and uses the transfer function from the combined Polish and Finnish sites. The Swiss-Norwegian-Polish training set (SNP TS) is based on the data from Norway (including Svalbard), Swiss Alps and Poland. It uses both the 3-component WA-PLS, and the artificial neural network (ANN) transfer function model (Table 1.2).

Table 1.2. Characteristics of the East-European and Swiss-Norwegian-Polish chironomid-based temperature training sets (TS).

	East-European TS	Swiss-Norwegian-Polish TS	
Number of chironomid taxa	142	134	
Number of lakes	212	357	
Latitude range	49.19–69.55 °N	79.8–46.1 °N	
Longitude range	14.51–30.13 °E	5.0–31.0 °E	
Elevation range	4–1624 m a.s.l.	4–2815 m a.s.l.	
Sampling water depth range	0.3–15.0 m	2.5–77.0 m	
Mean July air temperature range	11.3–20.1°C	3.5–20.0°C	
pH range	4.6–9.8	4.7–9.8	
Root mean squared error of prediction (RMSEP)	WA-PLS: 0.88°C	WA-PLS: 1.39°C	ANN: 1.34°C
Correlation coefficient (R^2_{jack})	WA-PLS: 0.88	WA-PLS: 0.91	ANN: 0.95

a.s.l. – above sea level

The chironomid data from the RP W3(2) profile was used for water trophic state reconstruction in the moat system (Chapter IV). The values of total phosphorus (TP) were derived using two geographically distant training sets (Table 1.3). The Finnish TS is based on the 4-component WA-PLS regression model (Luoto, 2011), while the British TS uses a one-component WA (Weighted Averaging) (inverse) model (Brooks *et al.*, 2001).

Table 1.3. Characteristics of the Finnish and British chironomid-based water trophic state training sets (TS).

	Finnish TS	British TS
Number of chironomid taxa	32	72
Number of lakes	51	44
Total phosphorus (TP) range (µg/l)	1.5–105	5–1162
Dissolved oxygen range (mg/ l)	0–14	0.1–9.6
Conductivity range (µS/cm)	8–220	28–724
pH range	4.5–8.3	5.6–8.6
Root mean squared error of prediction (RMSEP)	WA-PLS: 6.675 µg/l	WA: 2.19 µg/l
Correlation coefficient (R^2_{jack})	WA-PLS: 0.921	WA: 0.60

Aims and hypotheses

The main aim of this PhD thesis was to estimate the character and scale of natural and anthropogenic processes in small, lowland water bodies on the basis of subfossil midge assemblages. The analyses of chironomid remnants found in moats and palaeochannel sediments (combined with other proxies) also allows for completing the following goals:

1) provide a high-resolution reconstruction of climate in Luciąża River valley during Allerød and early Younger Dryas,
2) describe the environmental history of small water bodies (oxbow and moat) in the vicinity of the Rozprza motte,
3) estimate the human impact in the Middle Ages on the nearby aquatic ecosystems,
4) contribute to better understanding of the ecology and habitat complexity of the medieval moats during their functioning,
5) compare the complexity and diversity of Chironomidae assemblages in the moat and the oxbow,
6) examine the applicability of Chironomidae morphological functional traits in habitat reconstruction.

In order to meet the above research goals, the following hypotheses have been verified:

H1 The succession processes are faster in anthropogenic water bodies (moats) than in natural oxbow lakes located in the same area.

H2 Human activity had a strong impact on the Chironomidae assemblages in medieval moats. The inhabitants of the ringfort influenced the fauna of the moat system mainly by increasing the water trophic state.

H3 Even in such a small and shallow water body as a moat, the spatial differences in Chironomidae community composition were significant.

H4 Chironomidae assemblages in oxbow lakes are influenced mainly by long-term climate changes, whereas the midge community composition in a moat is determined mainly by local habitat-scale factors.

References

Andersen F. S. 1938. Spätglaziale Chironomiden. Meddelelser Dansk geologisk Forening 9, 320–326.

Andersen T., Cranston P. S., Epler J. H. 2013. Chironomidae of the Holarctic region: Keys and diagnoses. Part 1. Larvae. Insect Systematics and Evolution Supplements 66.

Andrzejewski A., Sikora J. 2018. Grodziska wczesnośredniowieczne Polski Centralnej. Archeologiczne badania nieinwazyjne z lat 2013-2016. Stowarzyszenie Naukowe Archeologów Polskich, Oddział w Łodzi, Instytut Archeologii Uniwersytetu Łódzkiego, Łódź.

Armitage P. D., Cranston P. S., Pinder L. C. V. 1995. The Chironomidae. Biology and Ecology of Non-biting Midges. Chapman & Hall, London.

Battarbee R.W. 2000. Palaeolimnological approaches to climate change, with special regard to the biological record. Quaternary Science Reviews 19, 107–124.

Beiger M. 2004. Owady minujące Polski. Klucz do oznaczania na podstawie min. Bogucki Wydawnictwo Naukowe, Poznań.

Beneš J., Kaštovský J., Kočárová R., Kočár P., Kubečková K., Pokorný P., Starec P. 2002. Archaeobotany of the Old Prague Town defence system, Czech Republic: Archaeology, macro-remains, pollen, and diatoms. Vegetation History and Archaeobotany 11(1): 107–120.

Birks H. H., Birks H. J. B. 2006. Multi-proxy studies in palaeolimnology. Vegetation History and Archaeobotany 15, 235–251.

Birks H. J. B., Heiri O., Seppä H., Bjune A. E. 2010. Strengths and weaknesses of quantitative climate reconstructions based on late-Quaternary biological proxies. Open Ecology Journal 3, 68–110.

Bitušík P., Hamerlík L. 2014. Príručka na určovanie lariev pakomárov (Diptera: Chironomidae) Slovenska. Časť 2. Tanypodinae. [Identification key for Chironomidae of Slovakia. Part 2. Tanypodinae.] Belianum. Vydavat. Univ. Matej Bela v Banskej Bystrici.

Brodersen K. P., Andersen N. J. 2002. Distribution of chironomids (Diptera) in low arctic West Greenland lakes: trophic conditions, temperature and environmental reconstruction. Freshwater Biology 47(6), 1137–1157.

Brodersen K.P., Lindegaard C. 1999. Classification, assessment and trophic reconstruction of Danish lakes using chironomids. Freshwater Biology 42(1), 143–157.

Brohan P., Kennedy J. J., Harris I., Tett S. F. B., Jones P. D. 2006. Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. Journal of Geophysical Research Atmospheres 111(D12), 12106.

Brooks S. J. 2003. Chironomid analysis to interpret and quantify Holocene climate change. In: Mackay A., Battarbee R. W., Birks H. J. B., Oldfield F. (Eds.), Global change in the Holocene. Hodder Arnold, London, 328–341.

Brooks S. J. 2006. Fossil midges (Diptera: Chironomidae) as palaeoclimatic indicators for the Eurasian region. Quaternary Science Reviews 25, 1894–1910.

Brooks S. J., Bennion H., Birks H. J. B. 2001. Tracing lake trophic history with a chironomid-total phosphorus inference model. Freshwater Biology 46 (4), 513–533.

Brooks S. J., Langdon P. G., Heiri O. 2007. The identification and use of Palaearctic Chironomidae larvae in palaeoecology. Quaternary Research Association Technical Guide 10.

Brooks S. J., Axford Y., Heiri O., Langdon P. G., Larocque-Tobler I. 2012. Chironomids can be reliable proxies for Holocene temperatures. A comment on Velle et al. (2010). The Holocene 22(12), 1495-1500.

Brown A.D., Pluskowski A.G. 2011. Detecting the environmental impact of the Baltic Crusades on a late medieval (13th-15th century) frontier landscape: palynological analysis from Malbork castle and hinterland, northern Poland. Journal of Archaeological Science 38(8), 1957–1966.

Camuffo D., Bertolin C. 2012. The earliest temperature observations in the world: the Medici Network (1654-1670). Climatic Change 111 (2), 335–363.

Chmielowska A. 1966. Sprawozdanie z badań wczesnośredniowiecznego kompleksu osadniczego w Rozprzy. Prace i Materiały Muzeum Archeologicznego i Etnograficznego w Łodzi, Seria Archeologiczna 13, 249–265.

Chmielowska A. 1982. Rozprza we wczesnym i późnym średniowieczu. Prace i Materiały Muzeum Archeologicznego i Etnograficznego w Łodzi, Seria Archeologiczna 29, 159–206.

Contreras-Lichtenberg R. 2001. Revision der westpaläarktischen Arten des Genus *Glyptotendipes* Kieffer, 1913 (Insecta: Diptera, Nematocera, Chironomidae), Teil 2: Sg. *Glyptotendipes* s. str. Kieffer, 1913 und Sg. *Trichotendipes* Heyn, 1993. Annalen des Naturhistorischen Museums in Wien 103 B, 417–451.

Courtney G. W., Cranston P. S. 2015. Section VI: Phylum Arthropoda. Order Diptera. In: Thorp J. H., Rogers D. C. (Eds.), Thorp and Covich's Freshwater Invertebrates. Volume I, Ecology and General Biology. Academic Press, London, UK, 1043–1058.

Cranston P. S. 1995. Introduction. In: Armitage P. D., Cranston P. S., Pinder L. C. V. (Eds.), The Chironomidae. Biology and ecology of non-biting midges. Chapman & Hall, London, 385–404.

Czeczuga B., Kossacka W., Niedźwiedzki E. 1979. Ecological changes in Wigry lake in the postglacial period. Part III. Investigations of the Chironomidae stratigraphy. Polskie Archiwum Hydrobiologii 26, 351–369.

Dearing J. A., Battarbee R. W., Dikau I. R., Larocque I., Oldfield F. 2006. Human– environment interactions: learning from the past. Regional Environmental Change 6, 1–16.

Deevey E. S. 1942. Studies on Connecticut lake sediments: III. The biostratonomy of Linsley Pond. American Journal of Science 240, 233–264.

Delettre Y. R. 2000. Larvae of terrestrial Chironomidae (Insecta: Diptera) colonize the vegetation layer during the rainy season. Pedobiologia 44, 622–626.

Dickson T. R., Walker I. R. 2015. Midge (Diptera: Chironomidae and Ceratopogonidae) emergence responses to temperature: experiments to assess midges' capacity as paleotemperature indicators. Journal of Paleolimnology 53, 165–176.

Eggermont H., Heiri O., Verschuren D. 2006. Fossil Chironomidae (Insecta: Diptera) as quantitative indicators of past salinity in African lakes. Quaternary Science Reviews 25, 1966–1994.

Eggermont H., Heiri O. 2012. The chironomid-temperature relationship: expression in nature and palaeoenvironmental implications. Biological Reviews 87, 430–456.

Elias S. A. 2010. The history of Quaternary insect studies. In: Advances in Quaternary entomology. Developments in Quaternary Sciences 12, 1–8.

Engels S., Self A.E., Luoto T.P., Brooks S.J., Helmens K.F. 2014. A comparison of three Eurasian chironomid-climate calibration datasets on a W–E continentality gradient and the implications for quantitative temperature reconstructions. Journal of Paleolimnology 51, 529–547.

Ferrington L. C. 2008. Global diversity of non-biting midges (Chironomidae; Insecta-Diptera) in freshwater. Hydrobiologia 595, 447–455.

Gams H. 1927. Die Geschichte der Lunzer Seen, Moore und Walder. International revue der gesamten Hydrobiologie und Hydrographie 18: 305–395.

GBIF.org 2019. GBIF Home Page. Available from: https://www.gbif.org [22 October 2019].

Giłka W. 2011. Analiza różnorodności faunistycznej ochotkowatych z plemienia Tanytarsini w Europie (Diptera: Chironomidae). Dipteron, Bulletin of the Dipterological Section of the Polish Entomological Society 27, 11–31.

Heiri O., Lotter A. F. 2005. Holocene and Lateglacial summer temperature reconstruction in the Swiss Alps based on fossil assemblages of aquatic organisms: a review. Boreas 34, 506–516.

Heiri O., Lotter A. F. 2010. How does taxonomic resolution affect chironomid-based temperature reconstruction? Journal of Paleolimnology 44(2), 589–601.

Heiri O., Brooks S. J., Birks H. J. B., Lotter A. F. 2011. A 274-lake calibration data-set and inference model for chironomid-based summer air temperature reconstruction in Europe. Quaternary Science Reviews 30, 3445–3456.

Imbrie J. D, Kipp N. G. 1971. A new micropaleontological method for quantitative paleoclimatology: Application to a late Pleistocene Caribbean core. In: Turekian K. K. (Ed.), The late Cenozoic glacial ages. Yale University Press, New Haven, 71–181.

IPCC 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu & B. Zhou (Eds.)]. Cambridge University Press.

Jaroń B. 1938. Szczątki roślinne z wczesnego okresu żelaznego w Biskupinie, Wielkopolska. In: Kostrzewski J. (Ed.), Gród prasłowiański w Biskupinie w powiecie żnińskim. Sprawozdanie z badań w latach 1936 i 1937 z uwzględnieniem wyników z lat 1934-1935. Instytut Prehistoryczny Uniwersytetu Poznańskiego, 1–30.

Jaroń B. 1939. Średniowieczne szczątki roślinne z wykopalisk w Gnieźnie. In: Kostrzewski J. (Ed.), Gniezno w zaraniu dziejów (od VIII do XIII wieku) w świetle wykopalisk. Biblioteka Prehistoryczna 4, 273–316.

Juggins S. 2009. Transfer functions. In: Gornitz V. (Ed.), Encyclopedia of Paleoclimatology and Ancient Environments. Springer, Dordrecht, Netherlands, 959–962.

Juggins, S. 2013. Quantitative reconstructions in paleolimnology: new paradigm or sick science? Quaternary Science Reviews 64, 20–32.

Juggins S., Birks H. J. B. 2012. Quantitative environmental reconstructions from biological data. In: Birks H. J. B., Lotter A. F., Juggins S., Smol J. P. (Eds.), Tracking environmental change using lake sediments. Volume 5: Data handling and numerical techniques. Springer, Dordrecht, 431–494.

Kittel P., Muzolf B., Płóciennik M., Elias S., Brooks S. J., Lutyńska M., Pawłowski D., Stachowicz-Rybka R., Wacnik A., Okupny D., Głąb Z., Mueller-Bieniek A. 2014. A multi-proxy reconstruction from Lutomiersk-Koziówki, Central Poland, in the context of early modern hemp and flax processing. Journal of Archaeological Science 50, 318–337.

Kittel P., Sikora J., Wroniecki P. 2015. The morphology of the Luciąża River valley floor in the vicinity of the Rozprza medieval ring-fort in light of geophysical survey. Bulletin of Geography. Physical Geography Series 8, 95–106.

Kittel P., Sikora J., Wroniecki P. 2018a. A Late Medieval motte-and-bailey settlement in a lowland river valley landscape of central Poland. Geoarchaeology 33(5), 558-578.

Kittel P., Sikora J. Antczak O., Brooks S. J., Elias S.A., Krąpiec M., Luoto T. P., Okupny D., Pawłowski D., Płóciennik M., Rzodkiewicz M., Stachowicz-Rybka R., Wacnik A. 2018b. The palaeoecological development and functioning of the Late Medieval moat – multiproxy research at Rozprza, Central Poland. Quaternary International 482, 131–156.

Kočár P., Čech P., Kozáková R., Kočárová R. 2010. Environment and economy of the early medieval settlement in Žatec. Interdisciplinaria Archaeologica – Natural Sciences in Archaeology 1, 45-60.

Koszałka J. 2000. Makroskopowe znaleziska roślinne z wczesnośredniowiecznych warstw kulturowych i osadów jeziornych w Gnieźnie rdzeń GN 22/XIII i SW 3/91. Studia Lednickie, 6, 389–416.

Koszałka J. 2014. Źródła archeobotaniczne do rekonstrukcji uwarunkowań przyrodniczych oraz gospodarczych grodu w Łęczycy. In: Grygiel R., Jurek T. (Eds.), Początki Łęczycy. T. 1, Archeologia środowiskowa średniowiecznej Łęczycy: przyroda, gospodarka, społeczeństwo. Muzeum Archeologiczne i Etnograficzne w Łodzi, 191–242.

Kotrys B., Płóciennik M., Sydor P., Brooks S. J. 2020. Expanding the Swiss-Norwegian chironomid training set with Polish data. Boreas 49, 89–107.

Kozłowska A. 1921. O zbożach kopalnych z okresu neolitu w Polsce. Rozprawy Wydziału Matematyczno-Przyrodniczego Polskiej Akademii Umiejętności. Seria III. Dział B 20, 1–20.

Kurek J., Cwynar L.C. 2009. The potential of site-specific and local chironomid-based inference models for reconstructing past lake levels. Journal of Paleolimnology 42, 37e50.

Lackmann A. R., Butler M. G. 2018. Breaking the rule: Five larval instars in the podonomine midge *Trichotanypus alaskensis* Brundin from Barrow, Alaska. Journal of Limnology 77, 31–39.

Langdon P. G., Ruiz Z., Brodersen K. P., Foster I. D. L. 2006. Assessing lake eutrophication using chironomids: understanding the nature of community response in different lake types. Freshwater Biology 51, 562e577.

Larocque I., Hall R., Grahn, E. 2001. Chironomids as indicators of climate change: a 100-lake training set from a subarctic region of northern Sweden (Lapland). Journal of Paleolimnology 26, 307–322.

Larocque I., Pienitz R., Rolland N. 2006. Factors influencing the distribution of chironomids in lakes distributed along a latitudinal gradient in northwestern Quebec, Canada. Canadian Journal of Fisheries and Aquatic Sciences 63, 1286e1297.

Lastochkin D. A. 1949. Ocherki po paleolimnologii Urala. Trudy Laboratorii Sapropelevykh Otlozheniy 3, 101–135.

Lindegaard C. 1995. Classification of water-bodies and pollution. In: Armitage P. D., Cranston P. S., Pinder L.C.V. (Eds.), The Chironomidae. Biology and ecology of non-biting midges. Chapman & Hall, London, 385–404.

Livingstone D. M., Lotter A. F. 1998. The relationship between air and water temperatures in lakes of the Swiss Plateau: A case study with paleolimnological implications. Journal of Paleolimnology 19, 191–198.

Lotter A. F., Birks H. J. B., Hofmann W., Marchetto A. 1998. Modern diatom, cladocera, chironomid, and chrysophyte cyst assemblages as quantitative indicators for the reconstruction of past environmental conditions in the Alps. II. Nutrients. Journal of Paleolimnology 19, 443e463.

Luoto T. P. 2009a. Subfossil Chironomidae (Insecta: Diptera) along a latitudinal gradient in Finland: development of a new temperature inference model. Journal of Quaternary Science 24, 150−158.

Luoto T. P. 2009b. A Finnish chironomid- and chaoborid-based inference model for reconstructing past lake levels. Quaternary Science Review 28, 1481e1489.

Luoto T. P. 2010. Hydrological change in lakes inferred from midge assemblages through use of an intralake calibration set. Ecological Monographs 80, 303e329.

Luoto T. P. 2011. The relationship between water quality and chironomid distribution in Finland – a new assemblage-based tool for assessments of long-term nutrient dynamics. Ecological Indicators 11(2), 255–262.

Luoto T. P., Salonen V.-P. 2010. Fossil midge larvae (Diptera: Chironomidae) as quantitative indicators of late-winter hypolimnetic oxygen in southern Finland: a calibration model, case studies and potentialities. Boreal Environment Research 15, 1e18.

Luoto T. P., Nevalainen L. 2017. Quantifying climate changes of the Common Era for Finland. Climate Dynamics 49, 2557–2567.

Luoto T. P., Nevalainen L., Salonen V.-P. 2012. Midge distribution patterns at multiple spatial scales in shallow Finnish lakes revealed through sedimentary records. Entomologica Fennica 23, 83–94.

Luoto T. P., Kaukolehto M., Nevalainen L. 2014. The relationship between water and air temperature in chironomid-based paleoclimate reconstructions: Records from boreal and subarctic Finland. The Holocene 24, 1584–1590.

Luoto T. P., Kotrys B., Płóciennik M. 2019. East European chironomid-based calibration model for past summer temperature reconstructions. Climate Research 77, 63–76.

Makohonienko M. 2014. Środowisko przyrodnicze i gospodarka w otoczeniu średniowiecznego grodu w Łęczycy w świetle analizy palinologicznej. In: Grygiel R., Jurek T. (Eds.), Początki Łęczycy. T. 1, Archeologia środowiskowa średniowiecznej Łęczycy: przyroda, gospodarka, społeczeństwo. Muzeum Archeologiczne i Etnograficzne w Łodzi, 95–189.

Mann M. E. 2002. The value of multiple proxies. Science 297, 1481–1482.

Menne M. J., Williams C. N., Gleason B. E., Rennie J. J., Lawrimore, J. H. 2018. The Global Historical Climatology Network Monthly Temperature Dataset, Version 4. Journal of Climate 31(24), 9835–9854.

Moldenhawer K. 1939. Szczątki roślinne z X wieku z wykopalisk na Ostrowie Tumskim w Poznaniu. Przegląd Archeologiczny 6(2-3), 222–231.

Moller Pillot H. K. M. 2009. Chironomidae larvae. Biology and Ecology of the Chironomini. KNNV Publishing, Zeist.

Moller Pillot H. K. M. 2013. Chironomidae larvae of the Netherlands and adjacent lowlands, Biology and Ecology of the aquatic Orthocladiinae, Prodiamesinae, Diamesinae, Buchonomyiinae, Podonominae, Telmatogetoninae. KNNV Publishing, Zeist.

Nazarova L. B., Self A. E., Brooks S. J., Solovieva N., Syrykh L. S., Dauvalter V. A. 2017. Chironomid fauna of the lakes from the Pechora River Basin (East of European part of Russian Arctic): ecology and reconstruction of recent ecological changes in the region. Contemporary Problems of Ecology 10, 350–362.

O'Brien C., Selby K., Ruiz Z., Brown A.G., Dinnin M., Caseldine C., Langdon P., Stuijts I. 2005. A sediment-based multiproxy palaeoecological approach to the environmental archaeology of lake dwellings (crannogs), central Ireland. The Holocene 15(5), 707–719.

Pape T., Blagoderov V., Mostovski M. B. 2011. Order Diptera Linnaeus, 1758. In: Zhang Z.-Q. (Ed.), Animal Biodiversity: An Outline of Higher-Level Classification and Survey of Taxonomic Richness. Zootaxa 3148, 222–229.

Pinder L. C. V. 1995. The habitats of chironomid larvae. In: Armitage P. D., Cranston P. S., Pinder L. C. V. (Eds.), The Chironomidae. Biology and ecology of non-biting midges. Chapman & Hall, London, 107–135.

Płóciennik M., Skonieczka M., Antczak O., Siciński J. 2018. Phenology of non-biting midges (Diptera Chironomidae) in peatland ponds, Central Poland. Entomologica Fennica 29, 61–74.

Porinchu D. F., MacDonald G. M. 2003. The use and application of freshwater midges (Chironomidae: Insecta: Diptera) in geographical research. Progress in Geography 27, 378– 422.

Quinlan R., Smol J. P. 2001. Chironomid-based inference models for estimating end-of-summer hypolimnetic oxygen from south-central Ontario shield lakes. Freshwater Biology 46, 1529–1551.

Rolland N., Larocque I. 2007. The efficiency of kerosene flotation for extraction of chironomid head capsules from lake sediments samples. Journal of Paleolimnology 37, 565–572.

Rosenberg D. M. 1993. Freshwater biomonitoring and Chironomidae. Netherlands Journal of Aquatic Ecology 26, 101–122.

Rossaro B., Pirola N., Marziali L., Magoga G., Boggero A., Montagna M. 2019. An updated list of chironomid species from Italy with biogeographic considerations (Diptera, Chironomidae. Biogeographia – The Journal of Integrative Biogeography 34, 59-85.

Ruiz Z., Brown A. G., Langdon P. G. 2006. The potential of chironomid (Insecta: Diptera) larvae in archaeological investigations of floodplain and lake sediments. Journal of Archaeological Science 33, 14–33.

Rymer N. 1978. The Use of Uniformitarianism and Analogy in Palaeoecology, Particularly Pollen Analysis. In: Walker D., Guppy J. (Eds.), Biology and Quaternary Environments. Australian Academy of Science, Canberra, 245–257.

Schmid P. E. 1993. A key to the Chironomidae and their instars from Austrian Danube region streams and rivers. Part I, Diamesinae, Prodiamesinae and Orthocladiinae. Federal Institute for Water Quality of the Ministry of Agriculture and Forestry, Wien.

Scott G. H. 1963. Uniformitarianism, the uniformity of nature, and paleoecology. New Zealand Journal of Geology and Geophysics 6, 510–527.

Self A. E., Brooks S. J., Birks H. J. B., Nazarova L., Porinchu D., Odland A.A., Yang H., Jones V. J. 2011. The distribution and abundance of chironomids in high-latitude Eurasian lakes with respect to temperature and continentality: development and application of new chironomid-based climate-inference models in northern Russia. Quaternary Science Reviews 30, 1122–1141.

Sikora J. 2007. Polska Centralna we wczesnym średniowieczu w świetle badań archeologicznych i osadniczych. Slavia Antiqua 48, 121–159.

Sikora J. 2009. Ziemie Centralnej Polski we wczesnym średniowieczu. Studium archeologiczno-osadnicze. Instytut Archeologii Uniwersytetu Łódzkiego, Łódź.

Sikora J., Kittel P., Wroniecki P. 2015. From a point on the map to a shape in the landscape. Non-invasive verification of medieval ring-forts in Central Poland: Rozprza case study. Archaeologia Polona 53, 510–514.

Smol J. P., Birks H. J. B., Lotter A. F., Juggins S. 2012. The march towards the quantitative analysis of palaeolimnological data. In: Birks H. J. B., Lotter A. F., Juggins S., Smol J. P. (Eds.), Tracking Environmental Change Using Lake Sediments, Volume 5: Data Handling and Numerical Techniques. Springer, Dordrecht.

ter Braak C. J. F., van Dam H. 1989. Inferring pH from diatoms: a comparison of old and new calibration methods. Hydrobiologia 178. 209–223.

Vallenduuk H. J. 2017. Chironomini larvae of western European lowlands (Diptera: Chironomidae. Keys with notes to the species. With a redescription of *Glyptotendipes (Caulochironomus) nagorskayae* and a first description of *Glyptotendipes (Caulochironomus) kaluginae* new species. Lauterbornia 82, 1–216.

Vallenduuk H. J., Moller Pillot H. K. M. 2007. Chironomidae Larvae of the Netherlands and Adjacent Lowlands. General ecology and Tanypodinae. KNNV Publishing, Zeist.

van Nieuwenhijzen A. 2017. *Psectrocladius (Psectrocladius)* larven. Macrofaunanieuwsmail 139.

Velle G., Brodersen K.P., Birks H.J.B., Willassen E. 2010. Midges as quantitative temperature indicator species: Lessons for palaeoecology. Holocene 20(6), 989–1002.

Walker I. R. 1991. Modern assemblages of arctic and alpine Chironomidae as analogues for late-glacial communities. Hydrobiologia 214, 223–227.

Walker I. R. 1995. Chironomids as indicators of past environmental change. In: Armitage P. D., Cranston P. S., Pinder L. C. V. (Eds.), The Chironomidae. Biology and ecology of non-biting midges. Chapman & Hall, London, 405–422.

Walker I. R. 2001. Midges: Chironomidae and related Diptera. In: Smol J. P., Birks H. J. B., Last W. M. (Eds.), Tracking environmental change using lake sediments, Volume 4: Zoological Indicators. Kluwer Academic Press, Dordrecht, The Netherlands, 43–66.

Walker I. R., Mott R. J., Smol J. P. 1991. Allerød-Younger Dryas lake temperatures from midge fossils in Atlantic Canada. Science 253(5023), 1010–1012.

Whitehouse N. E., Langdon P. G., Bustin R., Galsworthy S. 2008. Fossil insects and ecosystem dynamics in wetlands: implications for biodiversity and conservation. Biodiversity and Conservation 17(9), 2055–2078.

Woźniak S., Antczak-Orlewska O., Płóciennik M. 2018. Wykorzystanie larw ochotkowatych (Diptera: Chironomidae) w monitoringu potoków górskich. Dipteron 34, 52–59

Chapter II. The environmental history of the oxbow in the Luciąża River valley – Study on the specific microclimate during Allerød and Younger Dryas in central Poland

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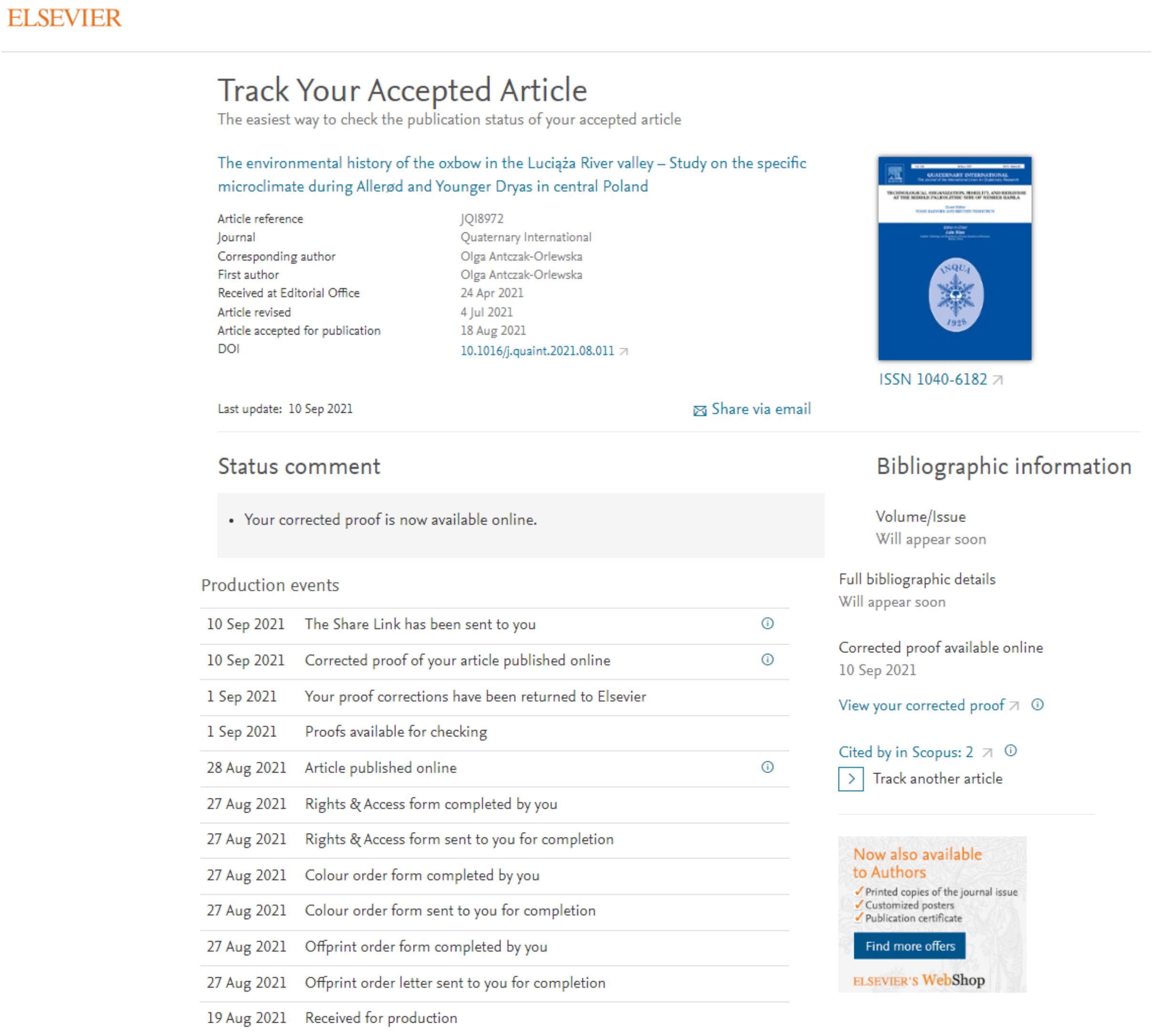

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The environmental history of the oxbow in the Luciąża River valley – Study on the specific microclimate during Allerød and Younger Dryas in central Poland

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ABSTRACT

The vicinity of the Rozprza archaeological site (central Poland) has been the area of a series of palaeoecological studies tracking the environmental history of the Luciąża River valley up to ca. 13,200 cal. BP. Numerous subfossil palaeomeanders of different sizes have been discovered in the valley floor. Here, we present the first results of multiproxy research on the paleo-oxbow lake fill, one of the oldest in the region. The wide range of palaeoecological analyses resulted in reconstructions of vegetation history, climatic, hydrological and habitat changes. The studied oxbow was an aquatic ecosystem with diverse invertebrate fauna until the end of Younger Dryas when it transformed into a limno-telmatic habitat. The sediment composition indicates active denudation processes and several episodes of turbulent hydrological conditions. Such an increased river activity could have caused flooding, resulting in an allochthonous matter supply to the oxbow lake in Late Vistulian. Environmental changes were strictly related to the regional features of the catchment, the transformation of soils, and the hydrogeological conditions. The chironomid- and pollen-inferred climatic reconstructions indicate periods of high and low continentality. The chironomid record indicates relatively cool summer conditions in the Allerød, especially ca. 13,000 cal. BP, possibly related to the Gerzensee Oscillation. On the other hand, a distinct increase of summer temperatures in Younger Dryas (up to 16 °C) was recorded. Such a situation was also confirmed in some other studies from the region, suggesting that it might be the effect of some specific, local palaeoclimatic conditions.

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1. Introduction

The multi-proxy approach is the most comprehensive way to achieve a reliable, holistic picture of the past environments. It helps to detect possible misinterpretations and improve environmental reconstructions (Mann, 2002). Biotic proxies play an important role in such studies especially in palaeohydrological reconstructions but also in tracking past climatic and other environmental changes (Smol et al., 2001a, 2001b; Birks et al., 2010; Vandenberghe and Sidorchuk, 2020). Plant macrofossils serve as good indicators of local habitat character, while pollen is useful to reflect the environment on the regional scale. However, vegetation often responds with some delay to rapid and short-term climate changes, whereas aquatic invertebrates are sensitive to even minor, local climate signals.

In recent years, the multi-proxy approach has been implemented in high-resolution research on palaeoclimate of Polish territory (e.g. Zawiska et al., 2015; Słowiński et al., 2016, 2017; Lamentowicz et al., 2019; Pleskot et al., 2020). Additionally, many studies in central Poland were undertaken on the palaeo-oxbow lakes, documenting the history of river valleys in the Late Vistulian (i.e. Rotnicki, 1988; Turkowska, 1988; Kozarski, 1991; Forysiak et al., 2010; Pawłowski et al., 2015a; Kittel et al., 2016; Płóciennik et al., 2016; Niska et al., 2017; Gałka et al., 2020).

Fluvial landscapes in Central Europe are characterised by small-size Holocene and large-size Vistulian meanders as the record of different discharge dynamics, often driven by climate changes (Turkowska, 1990; Starkel et al., 2013; Vandenberghe and Sidorchuk, 2020). Therefore, sedimentological and geochemical studies are crucial in the analysis of fluvial systems, as the water cycle, as well as the nature and intensity of transport of dissolved and suspended substances in the valley zone, are all influenced by the type, scale, and rate of denudation processes in the individual parts of the catchment area (Zwoliński, 1985; Gałka et al., 2020; Okupny and Pawłowski, 2021).

Vistulian sediments from the Łódź region (central Poland) are relatively well investigated, covering several sites (see Fig. 1B). Although most of them were studied comprehensively, the data resolution for climatic reconstructions was generally low. The nearest high-resolution site (with varved deposits) is Gościąż lake, localised ca. 100 km to the north from Łódź (Müller et al., 2021).

Hitherto, Late Vistulian history was investigated in the Luciąża River valley mostly using sedimentological methods (Wachecka-Kotkowska, 2004). The only site in the valley studied using various palaeoecological analyses and covering a similar timespan as the one at Rozprza is the Bęczkowice mire (Forysiak, 2012). Nevertheless, Rozprza is nowadays the best-studied site in the Luciąża River valley and one of the reference sites in the Łódź region. The multidisciplinary research conducted on the medieval settlement complex in Rozprza revealed information including human-environment interactions, moat system functioning, and the unique rampart construction (Kittel et al., 2018a, 2018b; Sikora et al., 2019). The human activity in the Late Palaeolithic has, however, only poor record in the vicinity of Rozprza. The single finds of flint tools may prove poor penetration of the area by small groups of hunter-gatherers. The present study is a part of the project, providing the environmental history of the valley evolution of the middle-reach Luciąża River.

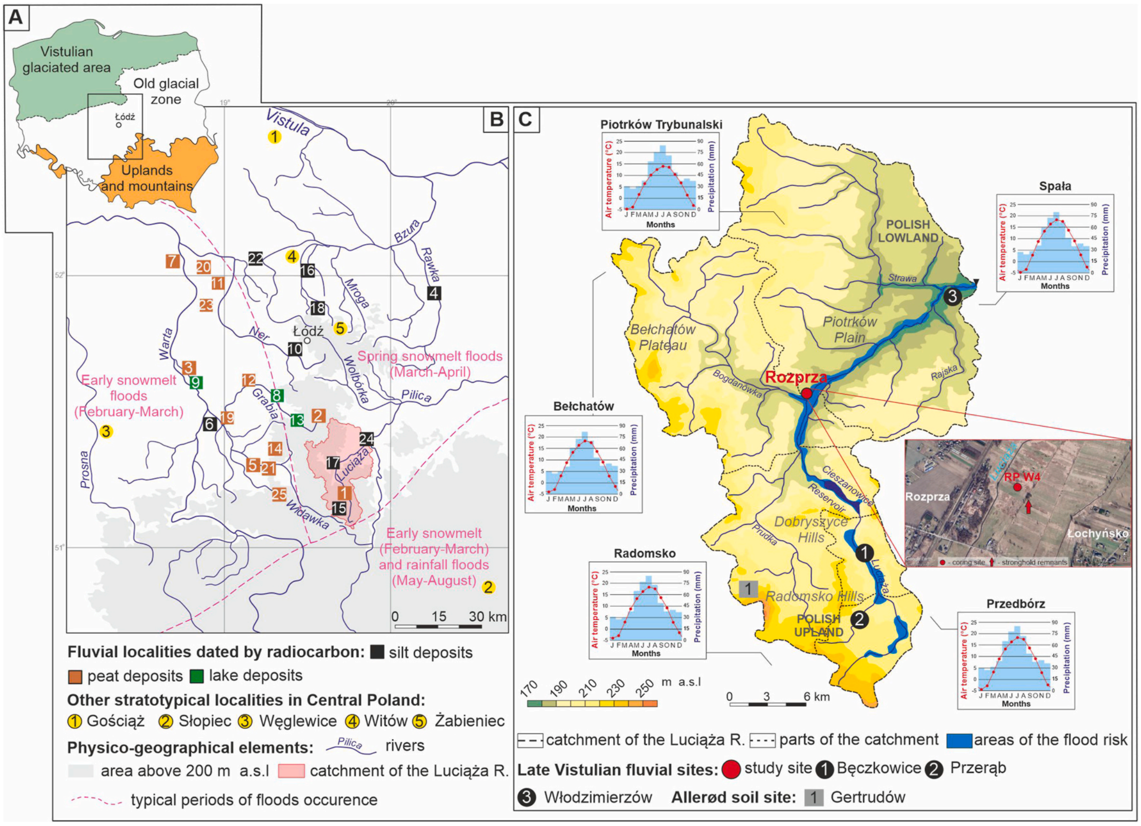


Fig. 1. A – Location of study deposits in the territory of Poland. B – The documented localities in central Poland with Allerød and/or Younger Dryas biogenic record against typical periods of floods occurrence after Biernat (1994): 1 - Bęczkowice, 2 - Grabica, 3 - Józefka, 4 - Kamion-Samice, 5 - Kowalce, 6 - Korzeń, 7 - Koźmin-Las, 8 - Ldzań, 9 - Ługi, 10 - Ner-Lublinek, 11 - Ner-Zawada, 12 - Okup, 13 - Pawłowa, 14 - Podwódka, 15 - Przerąb, 16 - Rogóźno, 17 - Rozprza, 18 - Swędów, 19 - Świerczyna, 20 - Świnice-Warckie, 21 - Trząs, 22 - Tum, 23 - Wilczków, 24 - Włodzimierzów, 25 - Wola Grzymalina (based on: Wasylikowa, 1964; Szczepanek, 1982; Rotnicki, 1988; Goździk and Konecka-Betley, 1992; Ralska-Jasiewiczowa et al., 2003; Dzieduszyńska, 2011; Forysiak, 2012; Marosik and Forysiak, 2014; Pawłowski et al., 2016; Stępień and Forysiak, 2017; Okupny and Pawłowski, 2021). C – satellite map of the investigated site, and other Late Vistulian sites against hypsometry and physico-geographical units of the Luciąża river catchment (after Manikowska, 1982; Wachecka-Kotkowska, 2004; Forysiak, 2012), contemporary range of the flood risk areas (after Hydroportal, 2015), and climate parameters (after Climate-Data.org) for selected stations.

The aims of this study are following: 1) to describe the development history of the oxbow during the Allerød and early Younger Dryas, 2) to present the high-resolution multi-proxy climatic reconstructions from this period for central Poland, and 3) to track the palaeohydrology and flooding events in the Luciąża River catchment. All these changes are discussed against global palaeoclimatic fluctuations, as well as regional characteristics.

2. Study area

Rozprza is a rural municipality in central Poland, located ca. 60 km SSE from Łódź, on the Piotrkowska Plain. The study site (51°18′07″ N; 19°40′04″ E; 182–183 m a.s.l.) is situated in the middle reach of the Luciąża River, which is a tributary of the Pilica River in the Vistula River basin (Fig. 1). Along its full course, the Luciąża and its tributaries cut through three morphogenetic units (Fig. 2), as reflected in the valley's features (Fig. 3). The Luciąża catchment is distinctly asymmetrical (from the river sources to the mouth to the Pilica River near Sulejów), the left-bank tributaries predominate. Generally, this region is characterised by a higher number of mires than other parts of central Poland (Żurek and Okupny, 2015).

The Luciąża River catchment is on the border area of rivers with high (e.g. Prosna, Grabia) and low runoff seasonality (e.g. Pilica). According to Jokiel and Stanisławczyk (2016), the first group includes rivers with a strongly developed nival system, while extensive, rich, and not very dynamic aquifers play an important role in supplying the second group of rivers (Fig. 2). In addition, the Luciąża River is characterised by the highest values of the highest maximum flow (WWQ = 86.8 m^3/s) and unit runoff (WWq = 173.7 $dm^3/s/km^2$) among other lowland rivers in Poland (Jokiel, 2015).

The region is part of the Odranian (Saalian) formerly glaciated area, and the last ice sheet was present there during the Wartanian Cold Stage of the Odranian Glaciation (Marks, 2011). The area is a part of the "European sand belt" (Zeeberg, 1998) characterised by wide-spread fluvial terraces and aeolian landforms. Intense transformation of river valleys took place there under periglacial conditions during the Vistulian (Weichselian) glacial period (Turkowska, 1988, 2006).

During detailed geological mapping, numerous subfossil palaeomeanders of different sizes have been discovered in the Luciąża valley floor in Rozprza (Kittel et al., 2015, 2018a) (Fig. 3). They reflect well the intense changes in the valley morphology throughout the last ca. 15,000 years. Whereas in the Late Vistulian there were large palaeomeanders, in the Holocene river channels were much smaller. Starting from the Middle Ages, several artificial channels and ditches were created in the Luciąża river valley (Kittel et al., 2018a). Nowadays, the channels of the Luciąża, Bogdanówka, and Rajska rivers are regulated.

The studied subfossil oxbow lake was a part of the large palaeomeander of the Luciąża River (or Bogdanówka River) (Kittel et al., 2018a). It was recorded as a strong curvilinear magnetic anomaly with a width of ca. 10 m, and a of radius ca. 15 m, visible in the field as a small depression periodically covered with water, as recorded in aerial photographs (Kittel et al., 2018a, 2018b).

Climatic conditions in the studied area are highly variable because of the influence of both oceanic and continental air masses. The average annual temperature from the last 30 years for the neighbouring station in Sulejów (ca. 20 km from Rozprza) is 8.6 °C, ranging from 6.7 °C (1996) to 10.3 °C (2019). The mean temperature of the warmest month (July) is 18.9 °C, while for the coldest month (January), it is −1.7 °C. The average annual precipitation reaches 570.7 mm, varying from 413.6 mm in 1991 to 830 mm in 2014 (Meteomodel.pl, 2019). Summer precipitation dominates in this region (35% of the yearly total), while the winter precipitation constitutes only 15%. Moreover, the relief of the Luciąża catchment causes variability in precipitation. The southern and western parts of the region, higher than 200 m a.s.l., receive an annual average of approx. 15% more than lower-lying areas, particularly in the north-eastern portion (Fig. 2).

3. Materials and methods

3.1. Fieldwork

In recent years, a detailed geological survey was carried out in the surroundings of the stronghold's remnants in Rozprza as an integral part of archaeological investigations (Kittel et al., 2015, 2018a, 2018b; Sikora et al., 2015a, 2015b, 2019). In order to document the surficial geology, approx. 340 cores were taken, using an Eijkelkamp hand auger

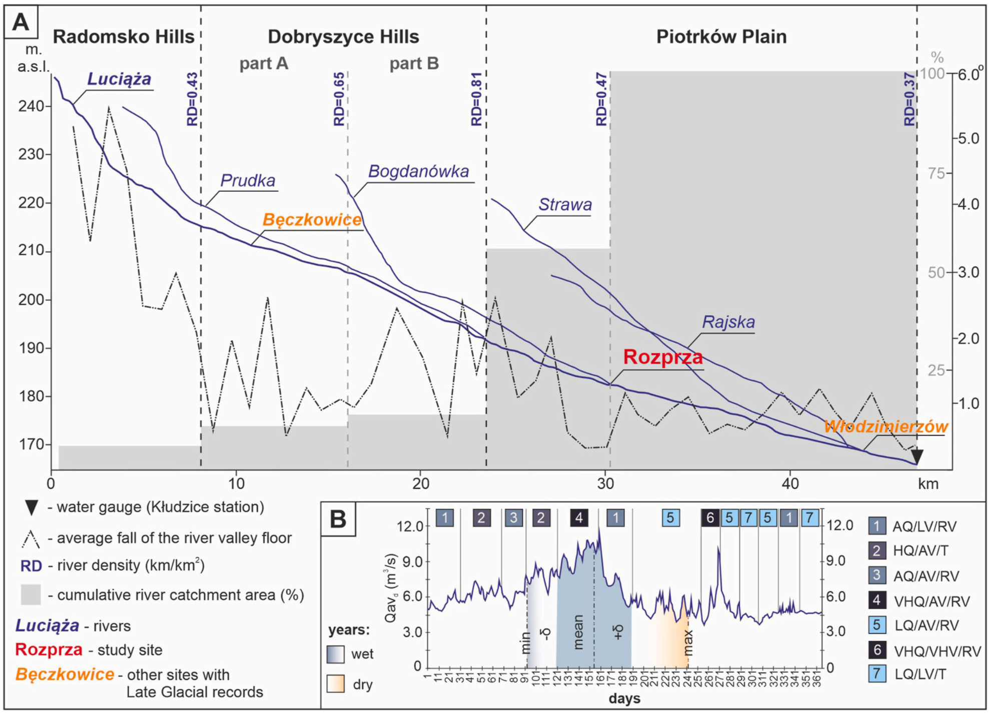


Fig. 2. A – Location of the study site indicated on river-long profiles of the Luciąża river system. B – Mean annual outflow hydrograph for the Luciąża River and its hydrological seasons in relation to multiannual variability to half-outflow terms (after Jokiel and Tomalski, 2015; Jokiel, 2016). LQ - low outflow, AQ - average outflow, HQ - high outflow, VHQ - very high outflow, LV - low variability, AV - average variability, VHV - very high variability, RV - random variability, T - trend. Min – earliest half-outflow term (92 day), Mean – mean half-outflow term (153 day), Max – latest half-outflow term (242 day).

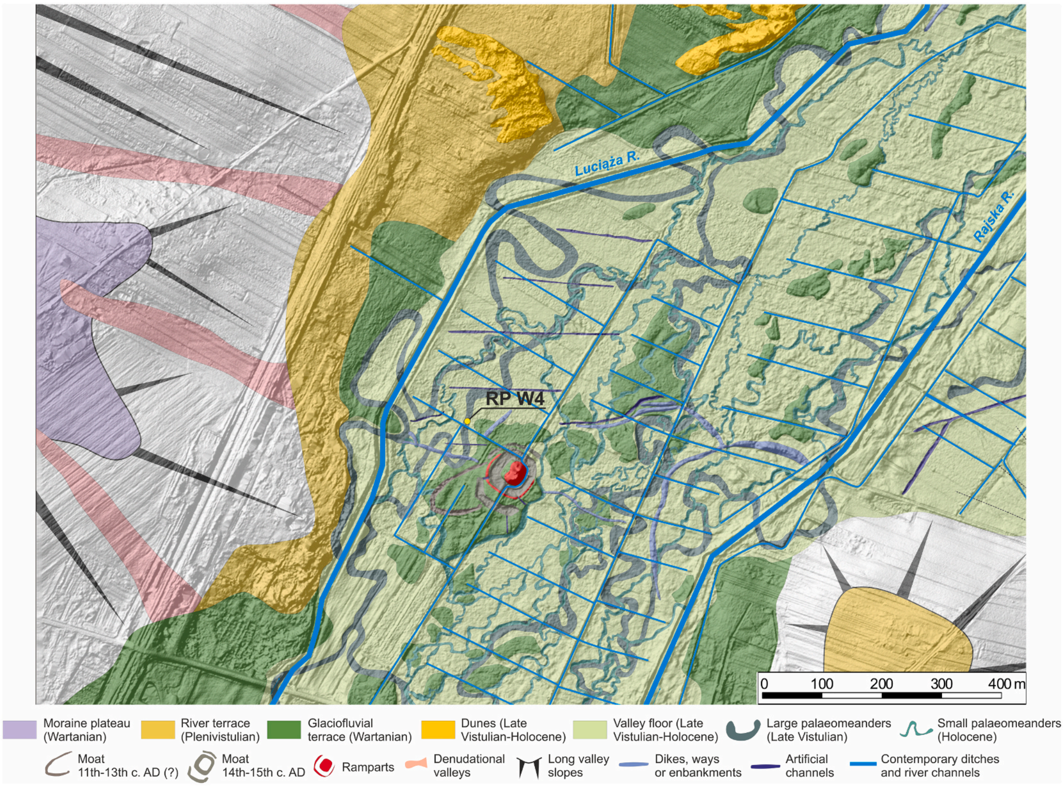


Fig. 3. The geomorphological map of the site vicinity (after Kittel et al., 2015, 2018a, modified).

at depths of 1.0–3.5 m.

For the study of the palaeochannel fill in detail, trench No. 4 was excavated with diameters of 2 × 10 m. Successive 10-cm layers of deposits were removed from the trench exposure, and excavated deposits were sifted and floated stratum by stratum with the use of a 4 × 4 mm sieve. Waterlogged layers were accessed by pumping water from the excavation.

The paleochannel fill consists of organic mud in the lower part and is overlain in the upper part by coarse detritus gyttja and peat with well-preserved fragments of wood and other plant macrofossils. The thickness of the paleochannel fill reached 130 cm, from ca. 90 to 210 cm below ground level (b.g.l.) (Fig. 4). It is underlain by channel alluvium of sands and gravels with organic mud laminations and plant detritus admixtures and overlain by the cover of overbank deposits of organic mud with sandy admixtures.

After a full excavation of trench No. 4, a core of organic deposits (RP W4) was collected in the deepest part of the palaeochannel cross-section. The core was collected as monoliths into five metal boxes with dimensions of 50 × 10 × 10 cm and covers deposits between 20 and 214 cm b.g.l. This method preserves the undisturbed structure of the sediments. Our study has been focused on the lowest part of the core between 172 and 214 cm b.g.l. correlated with the Late Vistulian.

3.2. Geochemical and sedimentological analysis

Chemical composition was determined in 22 samples taken every 2 cm after drying at 105 °C and homogenisation in an agate mortar. The basic lithogeochemical data for these samples were defined by identification of organic matter (loss on ignition method (LOI) in a muffle furnace for 6 h at a temperature of 550 °C), calcium carbonate – $CaCO_3$ (volumetric method using Scheibler's apparatus), reaction – pH (potentiometric method – in distilled water), biogenic and terrigenous silica – SiO_{2biog} and SiO_{2ter}, following the protocols described by Woszczyk et al. (2009) and Okupny et al. (2020). Ash samples were dissolved (with HCl, HNO_3, and H_2O_2) in Teflon bombs using a microwave mineraliser for 22 samples. The solution obtained was analysed for

Fig. 4. The lithology and organic matter content (presented as LOI – loss on ignition) of the RP W4 core, and a cross-section of the paleochannel fill – the southern wall of trench No. 4.

concentrations of Na, K, Ca, Mg, Fe, Mn, Cu, Zn, and Pb, using atomic absorption spectrometry, as defined by Borówka (1992). The results were expressed in g or µg of an element per 1g of dry mass. The proportions of these compounds can be used to classify deposits and to reconstruct environmental change in the sedimentologic basin and the catchment (Pawłowski et al., 2016; Gałka et al., 2020; Okupny et al., 2020). The grain size composition of the inorganic matter deposits and ash samples remaining after Loss-on-Ignition analysis was determined using the laser particle size analyser Mastersizer 3000 with a Hydro MU dispersion unit (Malvern). The textural features, using Folk and Ward (1957) coefficients and grain-size indicators (GSI1 as the ratio of coarse silt/fine silt content and GSI2 as the ratio of coarse silt to clay content) were calculated.

3.3. *Palaeoecological analyses*

3.3.1. *Pollen analysis*

Samples for palynological studies contained 1 cm^3 of sediment each. The analysis was performed at intervals of 4 cm. Chemical preparation of sediments for microscopic analysis, enabling the taxonomic determination of preserved fossil pollen and spores, followed the modified Erdtman's acetolysis method (Berglund and Ralska-Jasiewiczowa, 1986), including pre-treatment with 40% HF and HCl for the removal of inorganic components, silica and carbonates and KOH for removal of organic matter. For each of the 11 samples, at least two slides were examined under 400× and 1000× magnification. In order to estimate pollen concentrations *Lycopodium* tablets with a specified number of spores were added (Stockmarr, 1971). A minimum of 500 arboreal pollen grains (AP) and all accompanying pollen of terrestrial herbaceous plants (NAP), reed swamp, and aquatic plants, as well as spores of cryptogams, were counted per sample. Taxonomic identifications were carried out using keys, atlases (e.g. Beug, 2004; Reille, 1998), as well as the reference collection of the W. Szafer Institute of Botany, Polish Academy of Sciences in Krakow. The percentage values of taxa were calculated from the total sum which includes the sum of terrestrial plants pollen grains (AP + NAP = 100%). The pollen values of aquatic and wetland plants, as well as spores of cryptogams were determined on the basis of the total sum plus the number of the respective sporomorphs. The results are presented in a pollen diagram drawn on a metric scale with POLPAL for Windows software (Nalepka and Walanus, 2003). The estimation of changes in palynological richness was based on rarefaction analysis E (T minimal pollen sum) calculated using the application RAREF included in POLPAL (Nalepka and Walanus, 2003).

3.3.2. *Plant macrofossil analysis*

Plant macrofossils were analysed in 11 samples (80–100 cm^3 each) from the RP W4 profile. The samples were boiled with KOH in order to reduce the sediment content and remove the humic matter, and wet-sieved on a ϕ 0.2 mm sieve. The material remaining on the sieve was sorted under a stereoscopic microscope and marked under magnification ranging from 10× to 50×. Conservation of plant remains was done with a standard mixture of alcohol, water, and glycerine in a 1:1:1 proportion, with the addition of thymol. Fragments of plants were dried with 50% ethyl alcohol. Macrofossils were identified with the use of plant keys, atlases (Berggren, 1981; Cappers et al., 2006; Kats et al., 1965; Velichkevich and Zastawniak, 2006, 2008), a reference collection of modern seeds and fruits, and a collection of plant macrofossils housed in the Palaeobotanical Museum of the W. Szafer Institute of Botany, Polish Academy of Sciences, in Kraków. Individual taxa were assigned to habitat groups in the order of their appearance. The qualitative and quantitative results were presented in a diagram constructed with the use of POLPAL software (Nalepka and Walanus, 2003). The presence of the most numerous or characteristic taxa for a given level was considered when separating the levels.

3.3.3. *Chironomidae analysis*

The samples for chironomid analysis were taken as contiguous 2-cm slices of the sediment. The sample volume ranged between 1 cm^3 and 27 cm^3. Chironomidae preparation methods followed Brooks et al. (2007). The sediments were passed through a 56 µm mesh sieve. If head capsule concentration in the sediments was low, kerosene flotation was used following the methods of Rolland and Larocque (2007). Processed sediment was scanned under a stereo-binocular microscope. Where applicable, a minimum of 50 (preferably 100) chironomid head capsules from each sample were picked and mounted in Euparal®. Identification of chironomid head capsules follows keys by Schmid (1993), Brooks et al. (2007), and Andersen et al. (2013). Ecological preferences of identified taxa are based mainly on Brooks et al. (2007), Vallenduuk and Moller Pillot (2007), Moller Pillot (2009, 2013), and Luoto (2009). The midge sequence is presented in a stratigraphic diagram created with C2 software (Juggins, 2007). Chironomidae zonation was obtained using the "chclust" function from the Rioja package (Juggins, 2017) in R software (R Core Team, 2020). The zones were tested for statistical significance with the broken-stick model using the "bstick" function from the Vegan package (Oksanen et al., 2019).

3.3.4. *Cladocera analysis*

For Cladocera analysis, 1 cm^3 of fresh sediment samples taken at 4-cm resolution from RP W4 core were processed according to standard procedures (Frey, 1986). Initially, samples were treated with hot 10% KOH. The material was then deflocculated using a magnetic stirrer and sieved through a 50 mm mesh. The slides were prepared from 0.1 ml of each sample and examined with a microscope (100× magnification). The taxonomy of cladoceran remains in this paper follows that presented by Szeroczyńska and Sarmaja-Korjonen (2007). The ecological preferences of cladoceran taxa were determined on the basis of the published key after Bjerring et al. (2009).

3.4. *Climatic reconstruction methods*

The Chironomidae-inferred mean July air temperature was reconstructed using East-European (EE TS) (Luoto et al., 2019) and Swiss-Norwegian-Polish (SNP TS) (Kotrys et al., 2020) training sets. Only data from 214 to 180 cm b.g.l. was used, as the number of recorded chironomid head capsules in the remaining samples was too low (<50 individuals). The East-European training set (EE TS) is a combined calibration model based on the data from 212 sites located in Poland and Finland. It includes 142 Chironomidae morphotypes, and a temperature range of 11.3–20.1 °C. The 2-component WA-PLS model for the EE TS has a cross-validated correlation coefficient (R^2_{jack}) of 0.88 and a root mean squared prediction error (RMSEP) of 0.88 °C (Luoto et al., 2019). The SNP TS is based on 357 sites from Norway (including Svalbard), Swiss Alps, and Poland. It includes 134 Chironomidae taxa and has a 3.5–20.0 °C mean July air temperature range. The SNP TS uses not only WA-PLS, but also artificial neural network (ANN) transfer function. The RMSEP for the 3-component WA-PLS is 1.39 °C, while for the ANN it is 1.34 °C. R^2_{jack} is 0.91 and 0.95 respectively (Kotrys et al., 2020). The chironomid samples used in each reconstruction were classified according to the quality of the modern analogues. The samples remaining below the 2-percentile threshold of the training set dissimilarities were represented by very good modern analogues. For EE TS, this threshold was 7.24578 minDC, while for SNP TS WA-PLS – 6.98983 minDC. The samples below 5 percentile (EE TS: minDC <8.50537, SNP TS: minDC <8.57757) represented good modern analogues, and below the 10-percentile threshold (EE TS: minDC <9,75318, SNP TS: minDC <10.1025) – moderate modern analogues. All samples over this threshold were regarded as representing poor and very poor modern analogues.

Estimates of climatic parameters were calculated from pollen data using the Modern Analogues Technique (MAT) (e.g. Guiot, 1990). The MAT reconstructions are based on a database with over 3500 modern pollen spectra from Europe (Bordon et al., 2009) and the Mediterranean region (Dormoy et al., 2009), using the 4 modern assemblages with the smallest Chord distances. The pollen-inferred climate reconstructions were carried out with the biome constraint using the Rioja package (Juggins, 2017) in the R software (R Core Team, 2020).

3.5. Numerical analysis

Detrended Correspondence Analysis (DCA) was calculated for Chironomidae, Cladocera, and macrofossil assemblages in order to define the direction of assemblage variations in time. DCA was performed with R software (R Core Team, 2020), using the "decorana" function from the Vegan package (Oksanen et al., 2019) on the percentage data with down-weighting of rare species.

Principal Component Analysis (PCA) was used to reveal the relationship between lithology and variable geochemical proxies over time. Standardised values of the contents of LOI, SiO_{2ter}, eight macro- and microelements, and grain-size results for an inorganic admixture of sediments (M_z - median diameter, σ_1 - sorting, S_k - skewness, K_G - kurtosis, P_{10} diameter, and P_{90} diameter) were used as input variables. A scree plot of eigenvalues was used to determine the number of significant principal components (Dempster et al., 2012). In this study, the first three PCs are the most significant for the geochemical data set (eigenvalues >1), other PCs with eigenvalues <1 account for an increasingly small and insignificant amount of variance in the data, and thus are not used.

3.6. Radiocarbon dating and age-depth model

Seven samples of selected terrestrial plant macrofossils from the lower part of RP W4 core were dated with the radiocarbon (^{14}C) method using accelerator mass spectrometry technique (AMS) (Table 1). Samples were chemically pre-treated using the AAA (acid-alkali-acid) method. The organic samples were combusted, purified, and transformed into graphite (Nadeau et al., 1998) in the Laboratory of Absolute Dating in Cracow, Poland (Krąpiec et al., 2018a). The mixture of graphite and Fe powder was pressed into a target holder and measured with the AMS system at the Center for Applied Isotope Studies at the University of Georgia, USA (Cherkinsky et al., 2010).

Calibrated radiocarbon ages (cal yr BP) were made using the IntCal20 radiocarbon calibration dataset (Reimer et al., 2020) and the OxCal 4.4.2 calibration software (Bronk Ramsey, 2009).

The chronology (age-depth curve) of the RP W4 core is based on the OxCal P_Sequence model (Bronk Ramsey, 2008). In total five radiocarbon dates were used for the construction of the age-depth model between 173 and 210 cm of the core. Therefore, in our model, single-boundary constraints were introduced (Fig. 5). On the basis of the age-depth model, we calculated the probability distributions of the modelled calendar ages for 1-cm intervals of deposits.

4. Results and interpretation

4.1. Stratigraphy and chronology of palaeomeander fill

Organic mud lamination within channel alluvium was dated to 12,720 ± 80 BP, i.e. 15,281–15,051 cal. BP (Kittel et al., 2018a). This demonstrates that studied meandering river channel was active in the Oldest Dryas and Bølling, according to chronostratigraphic units proposed for the Łódź region by Dzieduszyńska (2019). Thus, it is one of the few earliest large-size meanders documented in the Łódź region during the Late Vistulian (cf. Pawłowski et al., 2016; Dzieduszyńska et al., 2020). Our study shows that Luciąża River close to Rozprza has shifted into meandering pattern earlier than Ner River (Turkowska, 1990; Turkowska and Dzieduszyńska, 2011) and in the similar period as Grabia River (Pawłowski et al., 2015a, 2016). The other sites in the transitional zone between uplands and lowlands in central Poland with Late Vistulian deposits have been dated accordingly to: 10,940 ± 100 BP at Przerąb and 10,920 ± 100 BP at Włodzimierzów (Wacheck-a-Kotkowska, 2004), 12,450 ± 150 BP at Bęczkowice (Forysiak, 2012), 11,970 ± 110 BP and 10,400 ± 100 BP in the Widawka River valley (Stępień and Forysiak, 2017), and range between 13,070 ± 70 and 10, 160 ± 70 BP for Grabia River valley (Pawłowski et al., 2015b; Okupny and Pawłowski, 2021).

Simultaneously, the radiocarbon dating from the very bottom of the studied paleochannel (11,126 ± 82 BP, i.e. 13,112–12,926 cal. BP — Table 1 and 13,174–13,069 modelled cal. BP — Fig. 5) indicates that the cutting-off of the oxbow could have occurred during the Older Dryas or in the Early Allerød (acc. to Dzieduszyńska, 2019). The oxbow lake was then filled at a high rate until 12,397–12,097 cal. BP, as demonstrated by the modelled age (Fig. 5), i.e. until the early Younger Dryas. The ^{14}C

Table 1
The results of radiocarbon dating of the material from the studied part of the RP W4 core.

Dated deposits	Depth b.g.l. [cm]	Dated macrofossils	^{14}C age yr BP	Laboratory code	Calibrated age BP (68.2%)	Calibrated age BP (95.4%)
coarse detritus gyttja	176–178	*Pinus sylvestris* – fragments of needle	10,877 ± 31[a]	MKL-A3566	12,823–12,754	12,839–12,743
coarse detritus gyttja with sandy admixtures	184–186	*Pinus sylvestris* - 8 shoots and 5 bud scales; shrub buds undif. - 5; *Betula* sect. *albae* - 4 fruit scales	10,415 ± 26	MKL-A3933	12,479–12,109	12,583–12,101
peaty organic mud	188–190	*Pinus sylvestris* - 20 shoots; *Betula* sect. *albae* - 2 fruit scales and 3 fruits; *Betula nana* - 4 fruit scales and 2 fruits; *Filipendula ulmaria* - 1 seed; *Urtica dioica* - 1 seed	10,889 ± 35	MKL-A4681	12,823–12,760	12,885–12,745
peaty organic mud	194–196	*Pinus sylvestris* - 2 seeds and 20 shoots; *Betula* sect. *albae* - 2 fruit scales; *Carex* sp. trigonous - 1 fruit	11,029 ± 26	MKL-A3934	13,055–12,901	13,075–12,843
organic mud	200–202	*Pinus sylvestris* - 22 shoots and 2 needles; *Betula* sect. *albae* - 1 fruit scale and 1 fruit; *Betula nana* - 3 fruits	10,069 ± 27[a]	MKL-A4682	11,743–11,407	11,807–11,401
organic mud	204–206	*Pinus sylvestris* - 4 fragments of cone and 3 bud scales; *Betula* sect. *albae* - 2 fruit scales	11,404 ± 27	MKL-A3935	13,312–13,241	13,331–13,180
organic mud	208–210	*Pinus sylvestris* - 1 fragment of cone, 5 shoots and 2 fragments of needle; *Betula* sect. *albae* - 2 fruit scales and 5 fruits; *Betula nana* - 7 fruit scales and 6 fruits	11,126 ± 82	MKL-3503A	13,112–12,926	13,170–12,839
		Larch wood, sample D3 (Dendro lab. code 2ROZP6, 10 last tree-rings)	11,200 ± 90	MKL-3392	13,233–13,000	13,299–12,906
		Larch wood, sample D4 (Dendro lab. code 2ROZP8, 10 last tree-rings)	11,130 ± 100	MKL-3393	13,155–12,920	13,236–12,785

OxCal v4.4.2 Bronk Ramsey (2020): r.5 Atmospheric curve (Reimer et al., 2020).

[a] Dates not included into depth/age model, recognised as outliers (redeposited material).

Depth (cm b.g.l.)	^{14}C age yr BP	Unmodelled age (cal. BP)	Modelled age (cal. BP)	Indices A	Indices C
173			12,421-12,159 (68.2 %) 12,475-11,925 (95.4 %)		98.6
185	10,415±26	12,479-12,109 (68.2 %) 12,583-12,101 (95.4 %)	12,592-12,550 (68.2 %) 12,612-12,430 (95.4 %)	40.2	99.7
189	10,889±35	12,823-12,760 (68.2 %) 12,885-12,745 (95.4 %)	12,790-12,750 (68.2 %) 12,823-12,7442 (95.4 %)	102.4	99.9
195	11,029±26	13,055-12,901 (68.2 %) 13,075-12,843 (95.4 %)	12,938-12,844 (68.2 %) 12,978-12,837 (95.4 %)	99.6	99.1
209	11,126±82	13,112-12,926 (68.2 %) 13,170-12,839 (95.4 %)	13,174-13,069 (68.2 %) 13,300-13,020 (95.4 %)	75.5	98.8
210			13,208-13,079 (68.2 %) 13,327-13,032 (95.4 %)		98.2

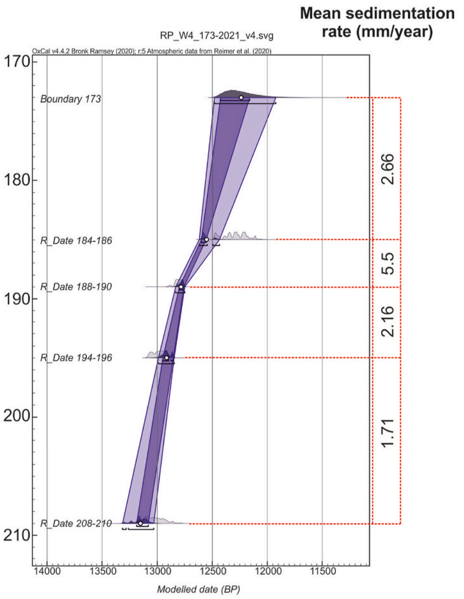


Fig. 5. The P_Sequence depth/age model for the studied part of the RP W4 core.

data from a depth of 160–165 cm of the core (7800 ± 50 BP, 8638–8520 cal. BP) shows depositional hiatus from late Younger Dryas to Early Holocene. The basin was then filled with coarse-detritus gyttja and peat and existed at least up to 3270 ± 40 BP, i.e. 3559–3449 cal. BP, as shown by the ^{14}C date from the depth 90–95 cm b.g.l. Later, since 2230 ± 50 BP (2324–2155 cal. BP), overbank accumulation took place within periodically existing backswamps in the Subatlantic period (Kittel et al., 2018a).

The main period of the oxbow lake development studied in the paper covers Allerød and early Younger Dryas from ca. 13,200 to ca. 12,200 cal. BP (Fig. 5). Two more subfossil palaeochannels dated to the Bølling-Allerød chronozone were documented eastward from the stronghold (Kittel et al., 2018a). Thus, it is not certain whether the studied palaeochannel was of the Luciąża River branch or its tributary Bogdanówka River.

4.2. *Biostratigraphy*

The pollen sequence within the studied part of the RP W4 core is consistent, creating one zone (Fig. 7). In the plant macrofossil sequence, three L MAZ levels are distinguished: RP-1 from 214 to 200 cm b.g.l., RP-2 from 200 to 176 cm b.g.l., and one outlier sample from the depth 172–174 cm, creating a separate zone RP-3 (Fig. 8). Chironomidae RP W4 sequence is divided into three significant zones (Fig. 9). The first part of the oxbow evolution coincides with zone Ch1 (214–192 cm b.g.l.). Ch2 (192–178 cm b.g.l.) covers late Allerød and early Younger Dryas, up to the period of oxbow paludification. Ch3 zone (178–173 cm b.g.l.) includes three samples with very low head capsule concentrations. The studied Cladocera sequence is split into two zones: LCAZ R-1 (214–177 cm b.g.l.) and LCAZ R-2 (Fig. 10). The latter is created by one sample from the limno-telmatic period of the oxbow evolution (172–174 cm b.g.l.), coinciding with the Ch3 Chironomidae zone.

4.3. *Phases of oxbow evolution*

The phases presented below were distinguished on the basis of the depth/age model and correlated with the chronostratigraphy for the Łódź region proposed by Dzieduszyńska (2019).

4.3.1. *Phase I (Early Allerød; 13,200–13,050 cal. BP; depth 214–204 cm)*

At the onset of Allerød, the sand with organic admixture (LOI between 5.7 and 22.5%) was accumulated in the studied oxbow lake. The very low contents of lithophilic elements (Na - average 0.01 mg/g, K - average 0.03 mg/g, Mg - average 0.07 mg/g, and Fe - average 2.63 mg/g), documented at the depths of 214–210 cm and 206–204 cm, were interrupted with a sharp peak of almost all geochemical components between 210 and 208 cm, (13,100–13,000 cal. BP). The proportion of sand increased to 80–94%, and medium-grained sand dominates (average 46%). The dominance of coarse silt (two to three times) over fine silt indicates sediment transport under conditions of short-term suspension. The decrease of the PC1 axis was caused by the lowest content of organic matter and poor bioaccumulation of metals (Fig. 6).

Palynological data shows a very high frequency of arboreal taxa (AP; mean value 84%), with a predominance of *Pinus sylvestris*-type pollen up to 71% (mean value ca. 65%) and *Betula* pollen up to 21% (mean value ca. 15%). Other arboreal taxa such as *Salix* (up to 0.6%), *Larix, Populus, Juniperus, Betula nana*-type, and *Ephedra fragilis*-type are recorded as sporadic finds. Pollen grains of mesophilous trees and shrubs (*Corylus, Ulmus, Quercus*) occur but with total values below 2%. Representation of herbaceous taxa (NAP) is stable ca. 16% and its value is composed mainly by Cyperaceae (up to 11%), Poaceae (up to 4%), *Artemisia* (up to 1.8%), *Filipendula* (up to 1.7%), and Apiaceae pollen (up to 1.1%). Chenopodiaceae, Rubiaceae, *Rumex acetosella*-type are regularly noted while *Bupleurum, Gypsophila*, as well as spores of cryptogams such Filicales monolete, *Equisetum*, and *Sphagnum,* occur in single spectra (Fig. 7).

The results of the plant macrofossils analysis also showed the presence of trees and shrubs remains, including fruits, fruit scale of *Betula nana* and *B.* sect. *albae*, fragments of cones, needles, shoots, and bud scales of *Pinus sylvestris.* The last ones were the most numerous. Only one fruit of *Hippophaë rhamnoides* was found at this phase. Among terrestrial vegetation, the fruit of *Urtica dioica* was present. The marshy plant remains not only included species of the *Carex* genus such as *Carex elata*, *C. rostrata*, *C. vesicaria*, *C.* sp. biconvex*,* but also *Eleocharis palustris* fruits, *Comarum palustre,* and *Menyanthes trifoliata* seeds. Aquatic and swamp plants were represented by the infrequent fruits of *Oenanthe aquatica*, *Hippuris vulgaris,* and seeds of *Phragmites australis*. Sclerotia of *Cenococcum geophilum*, buds, scars, and fragments of wood were found in high numbers as well (Fig. 8).

Four fragments of fallen tree trunks were found in the bottom part of the palaeomeander fill (Fig. 4). Three of them represented larch (*Larix decidua* Mill.), and the fourth fragment – Scots pine (*Pinus sylvestris* L.).

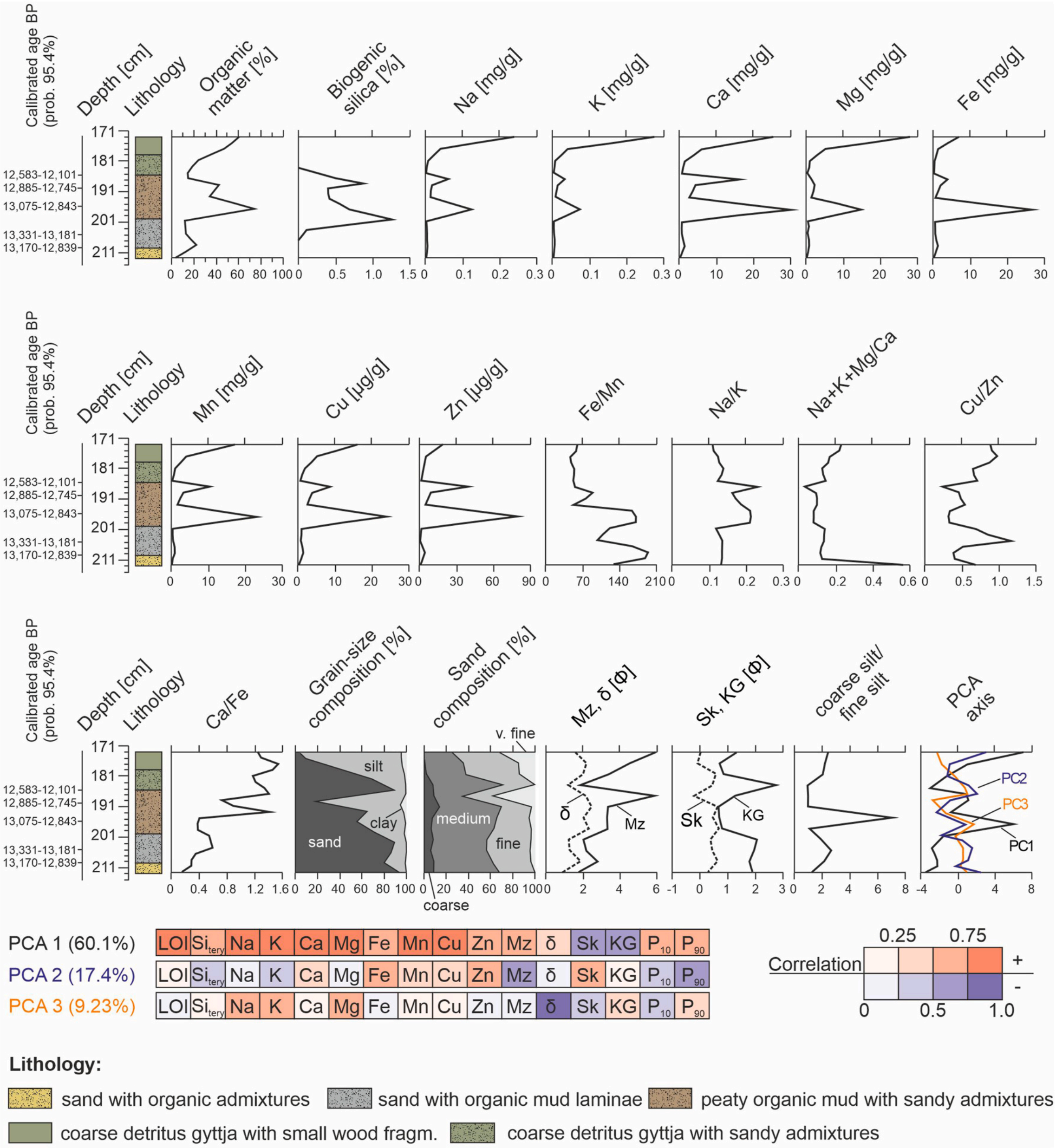


Fig. 6. Results of the geochemical and sedimentological analysis of the RP W4 deposits against the results of PCA. For detailed lithology see Fig. 4.

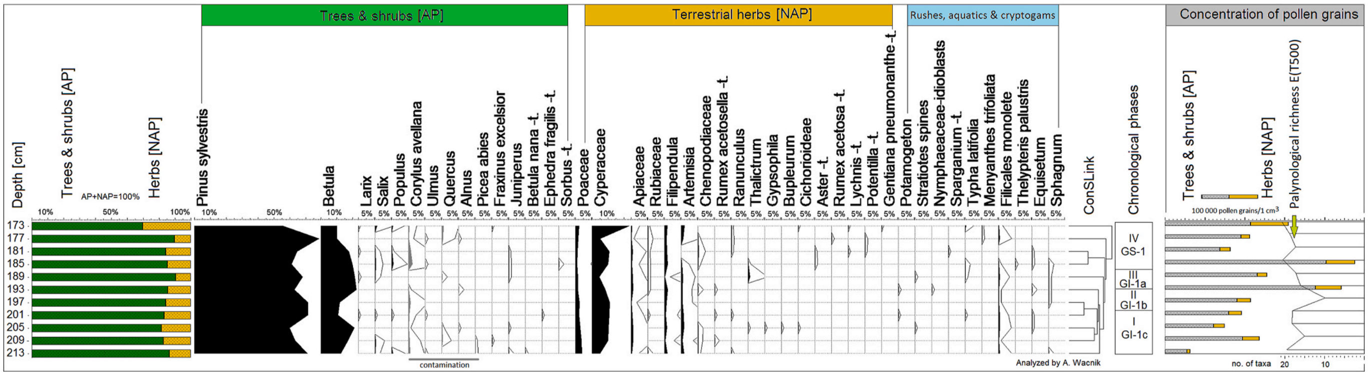
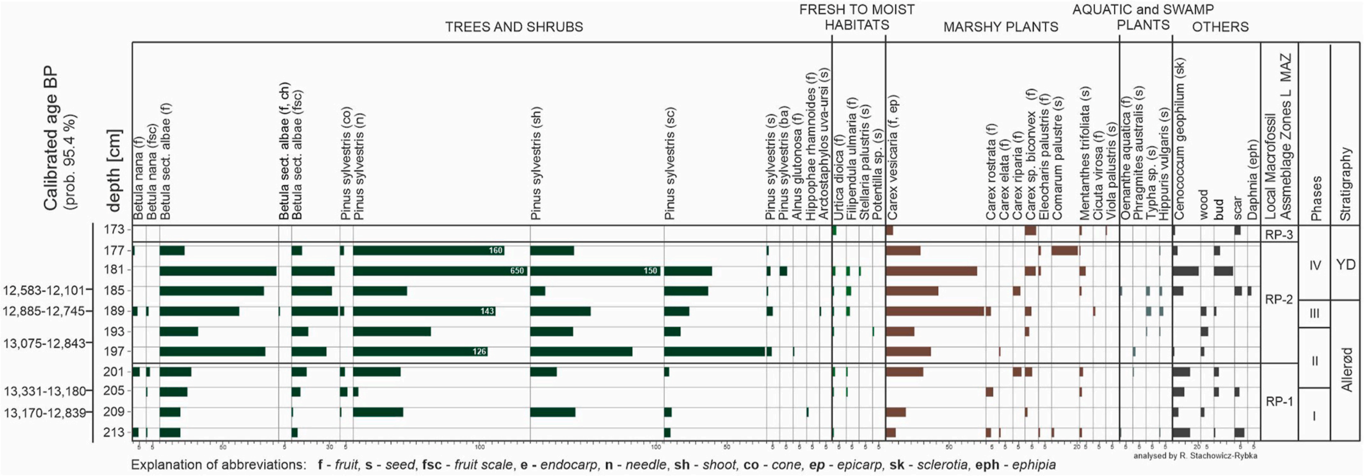


Fig. 7. Percentage pollen diagram from Rozprza, RP W4 profile, presenting the concentration of pollen grains.



Explanation of abbreviations: **f** - *fruit*, **s** - *seed*, **fsc** - *fruit scale*, **e** - *endocarp*, **n** - *needle*, **sh** - *shoot*, **co** - *cone*, **ep** - *epicarp*, **sk** - *sclerotia*, **eph** - *ephipia*

Fig. 8. Diagram of plant macrofossil remains recorded in RP W4 profile.

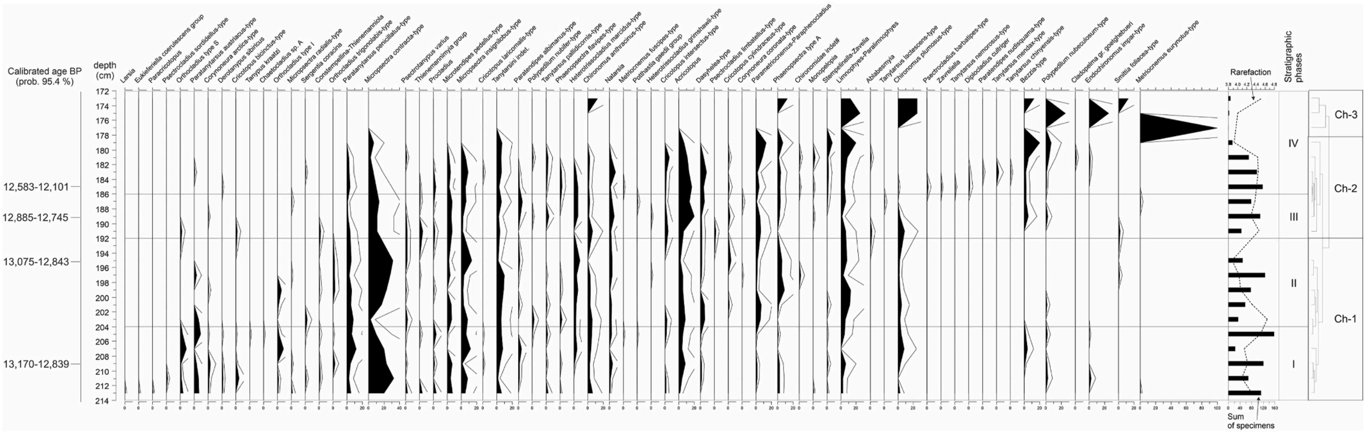


Fig. 9. Percentage Chironomidae stratigraphic diagram for the RP W4 profile.

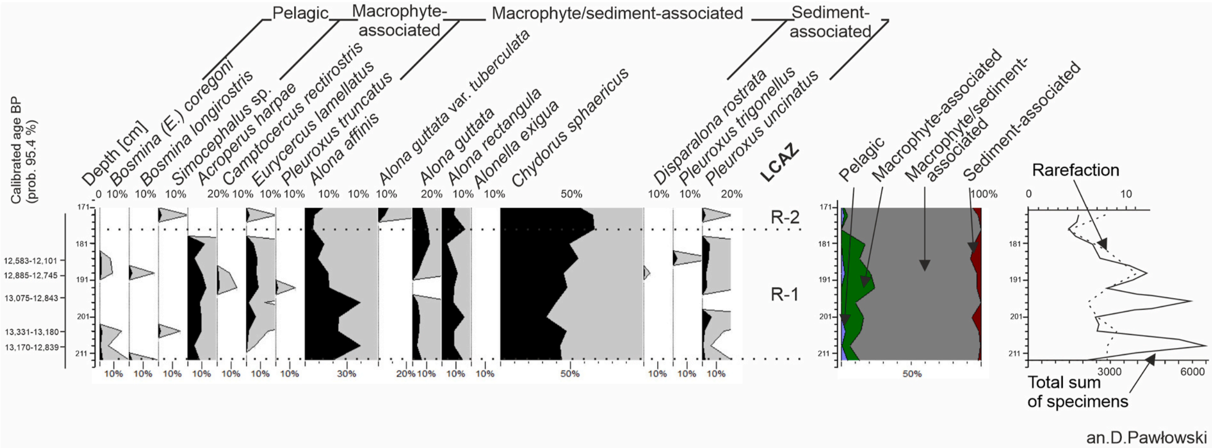


Fig. 10. Cladocera stratigraphic diagram for the RP W4 profile.

Two larch stems marked D3 and D4 contained more than thirty tree rings which allowed dendrochronological analysis. The dendrochronological sequences of these trees indicate that they most likely fell two years apart. Radiocarbon dating of the outer tree-rings (Table 1) indicates that the larches were felled in the time interval 13,170–12,900 cal. BP. This result is consistent with the dating of the sediments in which they lie, based on other organic samples (cf. Table 1).

This part of the profile is characterised by the highest chironomid and cladoceran abundance and diversity within the whole section. Within Chironomidae, the high prevalence of mineral bottom-dwellers (mainly *Micropsectra* spp.) was recorded. Such taxa found favourable conditions in the recently cut oxbow lake and constituted the crucial element of the first macrobenthos assemblages. Among them, some chironomids associated with lotic habitats were also recorded, such as

Paracricotopus, Thienemannimyia group, and *Larsia*. Their presence might have been caused by the presence of seepages or episodic connection of the oxbow lake to the main Luciąża (or Bogdanówka) channels (Howard et al., 2010) in the early stage of its functioning. Many taxa represented in this phase are cold-stenotherms (e.g. *Derotanypus sibricus, Corynoneura arctica*-type, *Sergentia coracina*-type*, Orthocladius trigonolabis*-type), indicating cool conditions in the early Allerød in the Luciąża river valley (Fig. 9).

This phase is composed mainly of macrophyte/sediment-associated cladocerans such as *Chydorus sphaericus*, *Alona affinis,* and *Alona rectangula*. Remains of pelagic forms such as *Bosmina (Eubosmina) coregoni*, *Bosmina longirostris*, and *Simocephalus* sp. and macrophyte-associated taxa: *Acroperus harpae, Eurycercus lamellatus, Alona guttata,* as well as sediment-associated taxa such as *Pleuroxus uncinatus* are recorded for the first time (Fig. 10).

4.3.2. Phase II (inter-Allerød oscillation; 13,050–12,850 cal. BP; depth 204–192 cm)

This period is associated with a change in lithology from sand with organic mud to peaty organic mud. It coincides with a very high organic matter content (LOI up to 83.4%), SiO_{2biog} (from 0.1 to 1.5%), and lithophilic elements (Na up to 0.31 mg/g, K up to 1.36 mg/g, Mg up to 0.87 mg/g and Fe up to 58.4 mg/g) concentration increase. The gradual change in the type of denudation processes corresponds to the grain-size composition of the inorganic admixture (an increase in the proportion of coarse silt from 5 to 30%). A twofold increase in values of the PC2 axis, which is correlated with Fe and Cu, suggests a periodic decrease of redox conditions (Fig. 6).

At the same time, single microremains of rush and water taxa, as *Potamogeton* (pollen), Nymphaeaceae (idioblasts), as well as Filicales monolete, *Equisetum*, and *Sphagnum* spores are found. This period is recorded by three pollen spectra in which most numerous was *Pinus sylvestris* increasing up to 71% in the upper spectra. Values of *Betula* strongly decrease from 22% to 12%. The reduction of the taxonomic diversity to only 10 pollen taxa was recorded at the depth of 197 cm (ca. 12,950 cal. BP). Pollen grains of Cyperaceae (up to 11%), Poaceae (up to 2.5%), and *Filipendula* (up to 2%) are numerous (Fig. 7).

As in the previous level, the remains of trees and shrubs were particularly numerous. *Betula* sect. *albae* and *Pinus sylvestris* dominated, but fruits and fruits scale of *B. nana* also were present. One *Alnus glutinosa* fruit was found only at this phase. Terrestrial vegetation was represented by infrequent fruit of *Urtica dioica*, *Potentilla* sp. and *Filipendula ulmaria*. The species such as *Carex elata*, *C. riparia*, *C. rostrata*, *C. vesicaria*, *C.* sp. biconvex, *Eleocharis palustris,* and *Menyanthes trifoliata* represented marshy plants communities. Among aquatic and swamp plants were the *Phragmites australis, Typha* sp. seeds and infrequent *Hippuris vulgaris* fruits (Fig. 8).

Chironomidae assemblages, particularly *Orthocladius trigonolabis*-type, *Heterotrissocladius marcidus*-type, *Thienemmannimyia* group, and *Micropsectra* spp., indicate a cooling episode in the second part of the phase, visible in each reconstruction (Fig. 10). Swampy conditions were preferable for some semiterrestrial taxa (e.g. *Limnophyes*, *Smittia foliacea*-type, *Natarsia, Parametricnemus-Paraphaenocladius, Dasyhelea*-type), that presumably inhabited *Sphagnum* mats in the shore zone of the oxbow lake (Fig. 9).

This time is also characterised by a systematic decrease of cladoceran frequency. While the pelagic forms of Cladocera disappear, the macrophyte- and macrophyte/sediment-associated taxa slightly increase, especially *Ch. sphaericus*, *A. affinis*, and *Ac. harpae* (Fig. 10). Most of them are cold-adapted taxa, tolerant to shallow river habitats (Robertson, 1990; Nevalainen, 2011; Pawłowski et al., 2015a, 2016). A similar situation is recorded in the chironomid assemblages.

4.3.3. Phase III (Late Allerød; 12,850–12,600 cal. BP; depth 192–186 cm)

This period is lithologically consistent with the previous one, organic matter content is relatively stable and high (LOI range 17–42%). A rapid change of grain-size composition in the sediment was documented from silty sand (Mz is 3.37 *phi*) to sandy silt (Mz is 5.86 *phi*), despite this value of the coarse/fine silt ratio is stable and does not exceed 1. The third PCA has positive loadings with lithophilic elements (Na, K, and Mg), and thus represents relative abundance delivery of detrital material to the basin (Fig. 6). Sediment composed from the peaty mud coincides with the presence of rush and marshy plants (*Sphagnum, Thelypteris palustris,* Filicales monolete*, Equisetum*, and *Typha latifolia*), as well as semi-terrestrial midges.

Phase III is represented by only a single pollen spectrum (from the depth of 189 cm) in the diagram, dominated by arboreal pollen (90%), mainly *Pinus sylvestris* (with value reaching 68%) and *Betula* (21%). *Larix, Salix*, and *Juniperus* are sporadic (values below 1% in total). The frequency of NAP is rather low with a predominance of Cyperaceae (4.6%), Poaceae (1.4%), *Thalictrum* (1.2%), *Artemisia,* and Apiaceae (both below 1%) (Fig. 7).

The results of plant macrofossil analysis also show that the tree stand surrounding the basin was still dominated by the *Betula* sect. *albae*, *B. nana*, and *Pinus sylvestris.* Single fruits of *Arctostaphylos uva-ursi* were also identified. Within terrestrial vegetation, *Urtica dioica*, and *Filipendula ulmaria* were observed. The frequency of peat plants increased strongly in comparison with the previous zones. Peat taxa included mainly *Carex vesicaria, C. rostrata, C.* sp. biconvex, and *Cicuta virosa.* Aquatic and swamp plants were represented by *Typha* sp. and *Hippuris vulgaris.* Fragments of wood and buds were recorded (Fig. 8).

Among Chironomidae, most of the cold-adapted taxa disappear, replaced by those typical to temperate conditions, such as *Polypedilum* spp., *Chironomus plumosus*-type, *Tanytarsus pallidicornis*-type, and *Cricotopus intersectus*-type. The share of the semiterrestrial taxa is still significant. An increased share of phytophilous taxa, mainly *Acricotopus,* is observed. Other representatives of the macrophyte-associated assemblage include species from *Ablabesmyia, Paratanytarsus*, *Corynoneura*, *Phaenopsectra,* and *Cricotopus* genera. (Fig. 9).

The zone is also characterised by an increase in cladocerans, especially pelagic taxa (mostly Bosminidae) and macrophyte-associated taxa. Most of the littoral species, especially chydorids (e.g. *Pleuroxus* spp., *Eurycercus lamellatus*, and *Camptocercus rectirostris*)*,* live in warm water, but they are also primarily associated with vegetation (Fig. 10).

4.3.4. Phase IV (Early Younger Dryas; 12,600–12,200 cal. BP; depth 186-173 cm)

The Early Younger Dryas is represented by the coarse detritus gyttja with increased content of organic matter (LOI from 16.4 up to 72.2%) and lithophilic elements, especially K (up to 3.1 mg/g) and Mg (up to 4.56 mg/g). The content of Ca and Mn were low and relatively invariant between 12,600 and 12,400 cal. BP. The inorganic admixture is characterised by relatively low content of fine and very fine sand (even below 6%), however, this section shows inverse grading sequence of Mz values (from 1.86 to 5.9 *phi*). This part of the core is characterised by gradually increasing values of the PC1 axis (interpreted as bio-accumulation processes), while at the same time stable but low values of the PC3 axis (interpreted as denudation processes) (Fig. 6). This geochemical stratification is consistent with well-documented records at other river valley mires from Central Europe (Niska et al., 2017; Okupny et al., 2019; Gałka et al., 2020; Okupny and Pawłowski, 2021).

The characteristic feature of Phase IV is a decreasing tendency of *Betula* pollen values (from 20% to 10%). After the initial strong increase of *Pinus sylvestris* pollen (up to 78% at a depth of 177 cm), its frequency decreased to 55%. *Larix* pollen reappears. *Salix* reaches up to 2.4%. Pollen grains of more thermophilous taxa such as *Corylus* (up to 2.4% in a single sample), *Fraxinus*, and *Quercus* are present (up to 2.6% in total). NAP pollen, especially Cyperaceae (up to 23%), *Artemisia* (up to 2.5%), Poaceae (up to 2.3%), *Filipendula* (up to 2%) are numerous. Other taxa such as Rubiaceae, Apiaceae, *Ranunculus*, Chenopodiaceae, and *Potentilla*-type pollen are regularly noted but do not exceed 1%. The presence of rush communities is marked by sporadic pollen of *Potamogeton*, *Sparganium*-type, and *Typha latifolia* as well as spores of *Equisetum* and Filicales monolete (Fig. 7).

The zone comprised numerous tree macrofossils, still dominated by the fruits and fruit scale of *Betula* sect. *albae,* as well as *Pinus sylvestris* fragments of cone, needles, shoots, and bud scales. *Betula nana* remains were recorded again. Terrestrial communities were still composed by *Urtica dioica*, *Filipendula ulmaria,* and *Stellaria palustris*. Proportions of peat plants were still high. This group was dominated by *Carex vesicaria, C. riparia, C. rostrata, C.* sp. biconvex*, Eleocharis palustris, Comarum palustre, Menyanthes trifoliata,* and *Viola palustris.* Aquatic and swamp plants were represented by the relatively frequent *Oenanthe aquatica, Typha* sp., and *Hippuris vulgaris.* Ephipia of *Daphnia,* buds, scars, wood fragments, and, at the bottom part of the phase, numerous sclerotia of *Cenococcum geophilum* were recorded (Fig. 8).

Mild temperatures are reflected not only in the vegetation record but also in the chironomid composition. Besides taxa typical to warm conditions (such as *Polypedilum* spp., *Chironomus plumosus*-type, *Cladopema lateralis*-type, *Tanytarsus pallidicornis*-type, and *Cricotopus intersectus*-type), in the first part of the phase (186–180 cm b.g.l.) several macrophyte-associated taxa were recorded (e.g. *Acricotopus* and *Endochironomus impar*-type). The end of the sequence was characterised by a significant drop of recorded head capsules, not exceeding 15, as well as the high share of semiterrestrial taxa (*Limnophyes, Parametricnemus-Paraphaenocladius,* and *Metriocnemus eurynotus*-type) (Fig. 9). This shift from aquatic to limno-telmatic conditions is reflected in the DCA Axis 1 (Fig. 11).

In the early Younger Dryas cladocerans systematically decreased as well. Although *Ch. sphaericus*, *A. affinis*, and *Ac. harpae* dominate, the presence of *Alona guttata* and *A. guttata* var. *tuberculata* at the end is also significant (Fig. 10).

4.4. Palaeoclimatic reconstructions

4.4.1. The Chironomidae-inferred mean summer air temperature reconstructions

The values of the Chironomidae-inferred mean July air temperature derived from Swiss-Norwegian-Polish TS using the Artificial Neural Network (Chiro_SNP TS_ANN_T Jul) vary from 11.6 °C (211 cm) to 16.1 °C (201 cm) (Fig. 11). The modelling using the same training set, but with WA-PLS method gives similar values, but a slightly narrower range: from 11.9 °C (207 cm) to 16.0 °C (181 cm). The EE TS reconstruction values vary from 12.6 °C (195 cm) to 14.7 °C (205 and 181 cm), presenting higher temperature amplitude and variability. Nevertheless, all three reconstructions reveal similar trends with the periods of cooling.

The SNP TS reconstructions indicate four phases (Fig. 11) of general summer mean temperature fluctuations. During the early Allerød (Phase I), summer mean air temperature oscillated near 13 °C with the cooling episodes at 211 cm (ANN) and 207 cm (ANN, WA-PLS) when it dropped below 12 °C. In the first part of Phase II (201 cm) mean temperature raised to 16.1 °C (according to ANN) or 14.8 °C (WA-PLS), and then gradually decreased, reaching 12.2 °C (ANN)/12.6 °C (WA-PLS) at 197 cm (12,983–12,892 cal. BP). The whole inter-Allerød cooling covers recorded at depths 200–194 cm (ca. 12,880–13,000 cal. BP) is characterised with the average SNP TS_T Jul of 12.9 °C (both methods). A short warming of 15.4 °C (ANN)/15.7 °C (WA-PLS) came in the late Allerød (189 cm), and in the early Younger Dryas, the SNP TS reconstructions indicate average CH-I Jul T of 15.4–15.5 °C. The EE TS reconstruction reveals in the late Allerød (Phase III) a similar trend to the one based on SNP TS (ANN). However, the temperature range calculated using EE TS for this period is generally higher (mean 13.9 °C). The inter-Allerød cooling overlaps with the one derived from SNP TS (200–194 cm; ca. 12,880–13,000 cal. BP) with the average T Jul of 13 °C. Phases III and IV are characterised by the gradual decrease of the summer mean air temperatures from 14.0 °C in late Allerød (192–188 cm) to 13.1 °C in the early Younger Dryas (179 cm), except for one sample at 181 cm (12,549–12,404 cal. BP), when the temperature value rose to 14.7 °C (Fig. 11).

Despite most of the samples having poor modern analogues, the cooling periods in WA-PLS reconstructions are supported with the moderate, good, or very good modern analogues (Fig. 11).

4.4.2. The pollen-inferred temperature of the coldest month and annual precipitation reconstructions

The pollen-inferred mean air temperature of the coldest month values ranges from −18.7 °C (201 cm) to −4.7 °C (191 cm) (Fig. 11). The annual precipitation reconstruction values range from 451 mm (193 cm) to 965 mm (185 cm). Both reconstructions indicate phases of higher continentalism (with cold winter and more dry conditions) during the transition to inter-Allerød oscillation (206–200 cm), as well as at the end

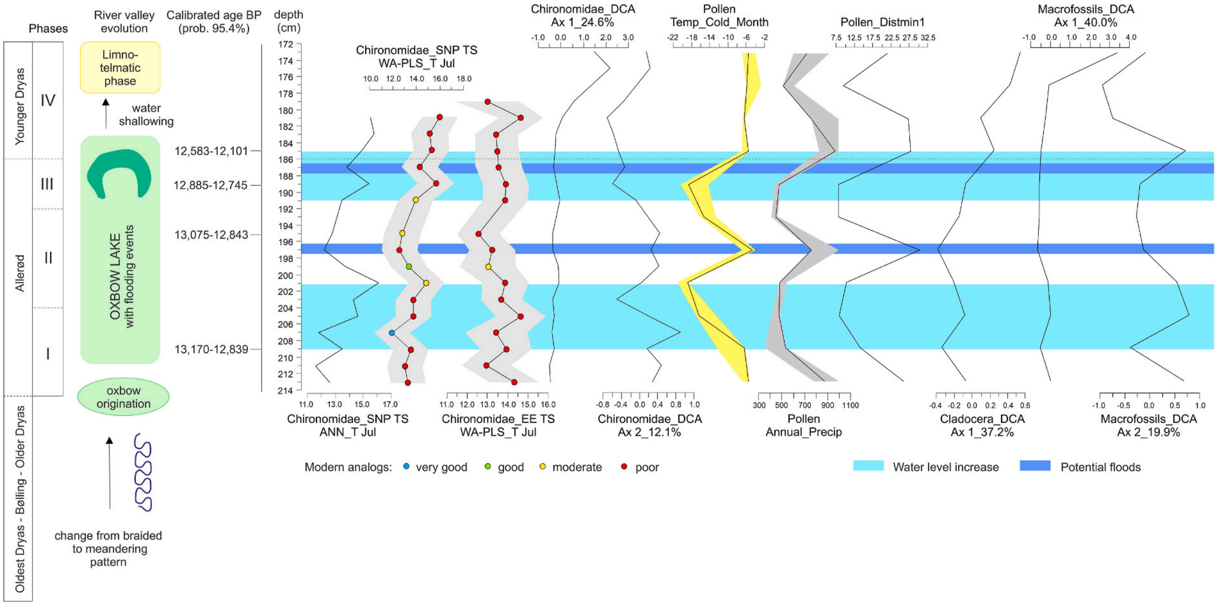


Fig. 11. The diagram presenting the river valley evolution in Rozprza, as well as the results of chironomid- and pollen-inferred quantitative climatic reconstructions, with the shaded area reflecting the error range. The DCA and Distmin1 graphs are presented as well.

of Phase II and in Phase III (late Allerød, 194-188 cm). The two phases of mild winters and high humidity indicate the high impact of oceanic climate. They are presented as peaks on the graphs at 213 cm, 197 cm, and 185–181 cm (Fig. 11). Samples 209 cm and 177 cm reveal mild winters and low annual precipitation.

5. Discussion

The oxbow lakes deposits are important archives of past environmental and climatic changes in Europe (Kołaczek et al., 2017; Gałka et al., 2020; Toonen et al., 2020). Although these lakes contain highly diverse and temporally variable biotic communities and geochemical items, oxbows are regularly flooded. Therefore, if we use oxbow sediments for fine stratigraphic resolution for the study, the hydroclimatic factors must be taken into consideration.

5.1. Environmental evolution of the catchment area

5.1.1. Allerød interstadial (phases I–III)

High arboreal pollen [AP] values above 80% are interpreted as an indicator of generally closed forests (e.g. Makohonienko et al., 1998; Święta-Musznicka, 2007). According to the obtained palynological data, the beginning of pollen accumulation in the sediments occurred when the area was covered with *Pinus sylvestris* forest with an admixture of woody birches. However, these communities typical of the Allerød were not very shaded as suggested by high light requirements of the mentioned taxa (Zarzycki et al., 2002). The Scots pine dominance was expressed by the average pollen values of approx. 65% (Fig. 7). It is assumed that values $>$ 50% indicate the dominance of pine in the composition of local forests (Huntley and Birks, 1983). The growth of both pine and birch in the immediate vicinity of a coring place was confirmed not only by significant pollen values but also by numerous finds of its macrofossils, starting from the Early Allerød (Fig. 8). Damp habitats favoured the development of communities with different species of *Salix*, *Populus* (probably *P. tremula*), *Betula* sect. *albae* and *Betula nana*. Some Poaceae, Cyperaceae, *Filipendula*, and *Thalictrum* would be associated with such habitats. Particularly interesting is the presence of the single *Alnus glutinosa* fruit in a sample from a depth of 196–198 cm in Rozprza. Few *Alnus* pollen grains are recorded in Late Glacial sediments of Poland, central and northern Europe (Latałowa and Borówka, 2006; Szczepanek et al., 2004; De Klerk, 2002). However, such findings are often interpreted either as contamination or as a result of long-distance transport. Nevertheless, *Alnus glutinosa* macrofossils indicate its local presence in this place. Meanwhile alder wood from Late Glacial peat layers in northwestern, southern and central Poland was reported (e.g. Wasylikowa, 1964; Szczepanek, 1971; Latałowa and Borówka, 2006). Therefore, it cannot be ruled out that *A. glutinosa* began to spread in Poland during Allerød. At that time *Larix* seemed to be a sparse component in forests. However, the large fragments of its trunks (ca. 13, 200–12,900 cal. BP) have been found in the palaeochannel fill. The presence of *Juniperus* and *Ephedra fragilis* confirms that these light-demanding shrubs grew locally in dry, sandy openings. Patches of open habitats (e.g. mid-forest gaps) were confined to small areas that were the source of pollen of different herbaceous taxa, such as representatives of Poaceae, Chenopodiaceae, Cichorioideae, *Artemisia*, *Gypsophila*, *Bupleurum*, and *Rumex acetosella*. The fact that only slight traces of corrosion of the pollen grain walls were found indicates favourable conditions for fossilisation, i.e. constant high level of substrate moisture. Remains of plants of floating leaves such as *Potamogeton* and Nymphaeaceae prove the functioning of the water reservoir at least partly overgrown with rush plants *Typha latifolia*, *Thelypteris palustris*, *Equisetum*, and *Sphagnum*.

The palaeobotanical and palaeopedological studies in Central Europe (Manikowska, 1997; Kaiser et al., 2006) show that during the periods of gradual improvement of climatic conditions in Late Vistulian, including the Allerød interstadial, the development of vegetation cover was accompanied by soil-forming processes. However, their intensity and degree of preservation depended on many factors that favoured or limited the accumulation of organic matter (Manikowska, 1982; Tolksdorf et al., 2014). The palaeobotanical results obtained for the studied profile confirm that relatively open landscape favoured intense physical weathering. This is also proven by the results of the concentration of lithophilic elements (Na, K, and Mg), which are an indicator of the relative changes in the weathering of aluminosilicates forming the substrate of the Luciąża basin, and the fluctuations in the share of SiO_{2biog}. As in the studied section of sediment was not found any evidence of diatoms nor sponges, the biogenic silica is conditioned here mainly by the concentration of orthosilicic acid H_4SiO_4 delivered to the reservoirs by surface water (slope wash processes). Probably an increased amount of these components was supplied mainly by the watercourses draining the western part of the catchment (Bogdanówka River and its tributaries), as according to Wetzel (1983), the lowest concentrations of silica are typical for surface waters in catchments built of carbonate rocks (in this case the southern part of the Luciąża catchment). On the other hand, a relatively high concentration of Ca (often between 20 and 30 mg/g), compared to other mineral-organic sediments filling river valleys in central Poland, may be related to the groundwater supply, and leaching of dissolved components from Quaternary bedrock in the highest parts of the catchment area with an average $CaCO_3$ content of 10–15% (Barczuk and Wachecka-Kotkowska, 2015). Moreover, the thickness of the drained profile of Quaternary sediments in the middle section of the Luciąża River valley is almost 50% greater than in the upper section (Fig. 3). Assuming a similar share of $CaCO_3$ in glacial and fluvioglacial sediments, more intensive leaching may apply to the Luciąża basin in the section from the northern part of Dobryszyce Hills to the studied site at Rozprza. A similar geochemical stratification was documented at the Bęczkowice site by Borówka et al. (2015), where relatively stable groundwater supply was interrupted during the periods of permafrost development in the substrate. All the above-mentioned factors also determined the distribution and migration of iron compounds, which is a very important element of the geochemical cycle, especially in the hypergenic zone (Wu et al., 2019). According to Wicik (2001), the waters of glial environments with the dominance of bicarbonate and calcium ions contain significant amounts of iron, mainly as $Fe(HCO_3)_2$. The concentration of Fe in the studied profile shows values typical for many sites of the Allerød fossil soil from central Poland (Manikowska, 1999), showing the strongest correlation with the share of organic matter between 13,075 and 12,843 cal BP. Moreover, during this period there is a clear decrease in Fe/Mn ratio, which proves changes in the intensity of weathering or reduction-oxidation processes.

5.1.2. Younger Dryas stadial (phase IV)

The deposition of the younger part of sediments took place during the last stadial of the Late Vistulian as confirmed by the radiocarbon date set. Pollen record revealed no significant change in the character of local vegetation. The area was still forested, and pine was the dominant component of the local forest communities initially, with a significant but decreasing share of birch. Only a few *Larix* and *Sorbus* cf. *aucuparia* grew in the surrounding forests. A similar phenomenon of the declining role of birches in the local vegetation accompanied by a growing share of Cyperaceae and Poaceae, which was interpreted as the result of an enlargement of open habitats was observed in the Koźmin-Las site at the beginning of Younger Dryas (Stachowicz-Rybka and Korzeń, 2014). In the studied profile from Rozprza (RP W4), a concentration of pollen reached the highest value at the beginning of the Younger Dryas and then was reduced. It was probable that pollen production was affected by plants' response to climate deterioration. However, pollen taxonomic richness remained at a similar level as in the early Allerød. The highest concentration of herbaceous plants in the upper sample reflected the expansion of sedges in the area. A similar character of vegetation as in the Rozprza region was described in several palynologically studied sites in central Poland, such as Żabieniec (Balwierz, 2010), Rąbień (Balwierz, 2011), Świerczyna (Pawłowski et al., 2015a), Pawłowa (Pawłowski et al., 2016), and Koźmin-Las (Stachowicz-Rybka and Korzeń, 2014). It is also consistent with the picture obtained from the isopollen maps drawn for this area (Ralska-Jasiewiczowa, 2004). In the case of the last-mentioned site, the dominance of pine pollen (average 50% share in the total), a presence of birch (average 8%), and significant shares of herbaceous plants, mainly Cyperaceae (average 20%) were recorded. The analysis of plant macrofossils showed a comparable number of pine and birch remains, confirming the loose nature of the stand at that time (Stachowicz-Rybka and Korzeń, 2014). In Witów site, the analysis of plant macrofossils also confirmed the local presence of pine and birch, although the palynological data indicated a higher opening of the communities (Wasylikowa, 1964). A regular occurrence of pollen grains of mesophilous trees such as *Corylus*, *Ulmus*, *Quercus*, and *Alnus* differs from the history of post-glacial migration of these taxa in the region (e.g. Ralska-Jasiewiczowa, 2004). It is probably due to the longer distance of pollen transport or contamination with younger material (cf. Stachowicz-Rybka and Korzeń, 2014).

At the end of the Younger Dryas, the oxbow started to paludify, the abundance of aquatic invertebrates dropped and among chironomids, the semi-terrestrial taxa started to dominate. The habitat change is reflected in the first DCA axes based on chironomid and plant macrofossil data (Fig. 11).

Among the many aspects discussed in the literature on environmental changes in Younger Dryas (Kaiser et al., 2012), attention should be paid not only to the intensity of the processes but also to their duration. The effects of the vegetation changes at the beginning of Younger Dryas are preserved in the form of dunes, denudation slopes, textural features of sediments, and the number of distinguished lithogeochemical facies (Turkowska, 1988; Forysiak, 2012; Okupny and Pawłowski, 2021).

5.2. *Flooding phases in the Luciąża River valley*

The flooding phases at the Luciąża River were recognised using geochemical and biotic records, especially aquatic invertebrates. The short-term increases in the frequency of Cladocera planktonic species may have resulted from periodic increases in the water level of the oxbow lakes (cf. Pawłowski et al., 2015a; Kittel et al., 2016; Płóciennik et al., 2016). We noted that these changes were correlated with the increased frequency of littoral sediment-associated Cladocera taxa. Besides, some benthic species of the Chydoridae family, such as *Acroperus harpae*, *Chydorus sphaericus* (sensu *lato*), occur in lakes and ponds can also occur periodically in flowing waters (cf. Robertson, 1990; Nevalainen, 2011). Similarly, head capsules of Chironomidae associated with lotic habitats in the sediment may be the record of the flooding events (Howard et al., 2010; Płóciennik et al., 2020).

The water level changes were noted in the early Allerød/inter-Allerød oscillation (after Dzieduszyńska, 2019), at ca. 13,100–13,000 cal. BP and in the late Allerød/early Younger Dryas, at ca. 12,800–12,500 cal. BP. Thus, the transition period, resulting from distinct global climatic changes, seems to reveal hydrological fluctuations, in particular an increase of flooding episodes in river systems (Starkel et al., 2013; Dzieduszyńska et al., 2014). They overlap with the occurrence of such chironomids, associated with fluvial habitats, as *Potthastia gaedii* group, *Corynoneura coronata*-type, and *Thienemannimyia* group (Fig. 9). Larvae of *Potthastia gaedii* group are truly rheophilic, most common in fast-flowing streams with a mineral bottom. *Corynoneura coronata* larvae prefer small watercourses (as brooks and ditches), but are macrophyte-associated, like most *Corynoneura* species (Andersen et al., 2013; Moller Pillot, 2013). *Thienemannimyia* group includes several taxa, many of them associated with running water, such as *Conchapelopia, Rheopelopia,* and *Thienemannimyia* (Vallenduuk and Moller Pillot, 2007; Bitušík and Hamerlík, 2014). Therefore, they can be used as the palaeoindicators of the water flow. Their presence could be the result of the inwashment from the main channel of the Luciąża and/or Bogdanówka rivers during floods. Similarly, the chironomid record also indicated flood activity in the Allerød/Younger Dryas transition in the Warta River valley (Petera-Zganiacz et al., 2015). Additionally, the aforementioned reorganisation in the composition and abundance of Cladocera is consistent with an increase in the content of mineral matter in the studied section (Fig. 10), which suggests that they might have resulted from floods. On the other hand, relative peaks of lithophilic elements (Na, K) suggest significant flood phases in the Luciąża River valley in the period between ca. 12,900 and 12,600 cal. BP. However, we have not noted cladoceran planktonic taxa at that time. Therefore, we have also assumed that high current velocities in the Luciąża River during flood phases were also likely to be the limiting factor for the high concentration of lithophilic items, as well as the reproduction of zooplankton such as Cladocera (cf. Pawłowski et al., 2016). Moreover, we suppose that fluctuations of the contents of soluble metals as Na and K reflected the input of these elements from the catchment area as the result of intense slope wash processes and flooding which could be a result of a combined flood wave increase from the Bogdanówka River valley into the Luciąża River valley.

The size and course of floods were determined by the physico-geographical parameters of the catchment (Figs. 2 and 3). The upper section of the Luciąża River is elongated (from its sources to the mouth of the Prudka River), and in the middle and lower section (from the mouth of the Prudka River to the Pilica River), the catchment area is compact. As a result, low and longer-lasting flood waves were overlapped with a supply of high flood waves of shorter duration. Among the determinants of the outflow and the course of morphodynamic processes, the regional differentiation of the surface structure of the declines and the exposure of the area played an important role. The most favourable conditions for rapid surface runoff of rainwater and meltwater, as well as limiting infiltration and evaporation, were probably in the upper part of the Luciąża River valley (within the Radomsko Hills) and its left-bank tributaries, mainly Bogdanówka, draining the highest parts of the Łódzkie Hills (often above 210 m a.s.l.). Similar observations were recognised in the region, from the Ślina (Oświt et al., 1980), Krasówka (Goździk and Konecka-Betley, 1992) and Grabia river valleys (Okupny and Pawłowski, 2021).

Floods from this period were also recognised in other river valleys from the region (Pawłowski et al., 2016) and Europe (Turner et al., 2013). Although in the late Allerød (ca. 13,500–12,600 cal. BP), fluvial activity decreases were recorded for the Jeetzel River valley (Turner et al., 2013). Also, the period of riparian forest development in the Koło Basin was indicated based on dendrochronological data to 13,110/13,070–12,910/12,860 cal. BP and the trees were overturned successively, over more than 100 years (Krąpiec et al., 2020). Wood remains were then covered with overbank alluvia after ca. 12,600 cal. BP (Kittel, 2015). The period of the riparian forest development can be correlated with the GI-1a phase after Rasmussen et al. (2014) or inter-Allerød oscillation after Dzieduszyńska (2019), and the period of flooding with GS-1 after Rasmussen et al. (2014) and the late Allerød/Younger Dryas transition after Dzieduszyńska (2019).

Similarly, in the early Younger Dryas, an increase in flooding was documented. A common increase in the water level at the study sites is comparable with those from the region (Wasylikowa, 2001; Pawłowski, 2012; Dzieduszyńska et al., 2014; Petera-Zganiacz et al., 2015; Kittel, 2015), southern Poland (Starkel et al., 2013), as well as from Central and Western Europe (Bohncke et al., 1993; Andres et al., 2001; Gao et al., 2007; Hoffmann et al., 2008), and Eastern Europe (Borisova et al., 2006). They all indicate flooding phases at ca. 13,500–11,500 cal. BP and resulted from a rapid cooling synchronous with GI-1 – GS-1 transition after Rasmussen et al. (2014).

The flooding phases derived from the Cladocera and geochemical record are to some extent consistent with the peaks in the pollen-inferred mean annual precipitation reconstruction (Figs. 10 and 11). Even though some delay within the pollen signal is observed compared to the Cladocera, it probably results from the well-known faster reaction of aquatic invertebrates to the environmental changes (Ammann et al., 2000; Birks and Ammann, 2000).

5.3. *Climatic conditions in central Poland during AL/YD transition*

The general trend of climate change after the Last Glacial Maximum was characterised by several cooling and warming events during the Late Vistulian (Słowiński et al., 2017; Müller et al., 2021). Changes in landscapes and hydrological systems caused then the development of mires in many river valleys (Żurek, 1990; Wójcicki, 2012; Forysiak, 2015; Wierzbicki et al., 2020). These aquatic ecosystems existed under an impact of active fluvial processes in floodplain basins or oxbow lakes and occupied mostly distal parts of valley floors or terrace depressions. The (geo)chemical composition of biogenic and mineral deposits from Late Vistulian palaeochannels is a useful indicator of climate changes (Kaiser et al., 2012; Pawłowski, 2017; Gałka et al., 2020).

Another indicator proxy are Chironomidae, sensitive to the summer temperature fluctuations (Birks et al., 2000; Brooks and Birks, 2001; Walker, 2001). Although both chironomid-based reconstructions derived for the Łódź region show similar trends in the mean temperature changes, the reconstructions based on SNP TS fit better to the reversed DCA axis 2 (Fig. 11). We can thus conclude, that mean summer air temperature was an important driver for Chironomidae assemblages. As the SNP TS combines chironomid data from the three different climatic regions, the reconstructions based on it reveal higher temperature variability. Mostly poor modern analogues in both reconstructions are the consequence of the studied ecosystem. Oxbow lakes within a river valley are rarely chosen as the source of samples included in training sets. Nevertheless, oxbows are shallow lakes, and temperature, mostly in summer, is a dominating driver of their communities in cold current climates (Nazarova et al., 2017), and during Late Vistulian in central Poland (Płóciennik et al., 2020). In Younger Dryas, regional oxbow' chironomid communities were sometimes dominated by *Corynocera ambigua* which obscure the chironomid inferred temperature reconstruction (i.e. Świerczyna - Pawłowski et al., 2015b). However, this is not the case of the midge communities of RP W4 core. Therefore, the Chironomidae-inferred mean summer air temperature reconstructions from Rozprza remain more reliable than from Świerczyna. The modern analogues are variable both for SNP TS and EE TS but reversed DCA Ax 2 coincides well with the reconstructed temperature trends.

The increasing temperature trend from Allerød to Younger Dryas seems to be surprising, as it is a well-documented cold event, especially in Europe (Carlson, 2010). Nevertheless, its impact was lower in the eastern part of the continent than in western Europe (Brooks and Langdon, 2014). The recent reconstructions from Gościąż lake indicate a cooling episode in the onset of Younger Dryas in Polish territories (Müller et al., 2021), but with relatively high summer temperature values for most of the period above 14 °C (SNP TS) or even 16 °C (EE TS). The records from Żabieniec are at a similar or even somewhat higher level (Kotrys et al., 2020). The values from Rozprza are not far from that, especially considering the reconstruction is based on EE TS. The chironomid-inferred July temperatures of ca. 15 °C reconstructed for the Younger Dryas are consistent with some recent studies (Birks and Birks, 2014; Schenk et al., 2018, 2020; Kubovčík et al., 2021). Although the increasing trend from Allerød may be puzzling, it is clear only from SNP TS reconstruction. The EE TS reconstruction from Rozprza gives rather cool inter-Allerød oscillation than the colder period from the Younger Dryas phase. It corresponds with the pollen record, where the taxonomic composition was significantly reduced in sample 197 cm, dated to the inter-Allerød oscillation. It cannot be ruled out that this was a reaction to a less favourable climate, as the chironomid record indicates in that time a distinct cooling (T July of 12–13 °C). This cool inter-Allerød oscillation might refer to the Gerzensee Oscillation, which has so far been recorded mainly in western Europe (e.g. Schwander et al., 2000; Ammann et al., 2013). This is also the first quantitative record of this event from East-Central Europe with the resolution that gives no doubts of the randomness of the results (Feurdean et al., 2014).

However, the chronostratigraphic phases of the Late Vistulian in central Poland according to Dzieduszyńska (2019) show distinct discrepancies in comparison with those derived from the Greenland ice-core isotopic analyses (Rasmussen et al., 2014). It is consistent with the well-recognised 100-200-year delay of the Younger Dryas onset in the western Europe record relative to Greenland Stadial 1 (GS-1) (Lohne et al., 2013; Obreht et al., 2020; Mangerud, 2021). The chronology of the laminated sediments from Gościąż and Perespilno lakes (Goslar et al., 1999; Müller et al., 2021) suggest that in Poland Younger Dryas started even later (i.e. 12,620–12,630 cal. BP). The cold inter-Allerød oscillation in central Poland (13,050–12,850 cal. BP) according to Dzieduszyńska (2019) overlaps with the warm GI-1a phase in the Greenland record (Rasmussen et al., 2014). Such differences may result not only from the regional specifics but also possible inaccuracies (Dzieduszyńska and Forysiak, 2019). It is worth notice that Dzieduszyńska (2019) used the former version of the calibration curve IntCal13 (Reimer et al., 2013), while the radiocarbon dates from this study were calibrated with the application of the most recent calibration curve IntCal20 (Reimer et al., 2020).

On the other hand, SNP TS reconstruction for the RP W4 profile gives warm oscillation on early GI-1a and generally cold Allerød compared to Younger Dryas, which is more consistent with DCA Ax 2. Such an unusual pattern may only be explained by the very local climatic conditions. Similar signals were recorded elsewhere in the region — from the mires in Żabieniec (67 km north from Rozprza – Płóciennik et al., 2011) and Bęczkowice (also located in Luciąża valley – Jakiel, 2013). This may suggest that local or regional climatic conditions in small depressions and river valleys could be specific to the Allerød due to unknown reasons like hydrology, permafrost phenomenon, or local geomorphology. Such a statement can be backed up by the record of subfossil riparian forests remains from the Allerød and Allerød/Younger Dryas transition known from Koło Basin in Warta River valley (Dzieduszyńska et al., 2014; Krąpiec et al., 2018b, 2020).

The chironomid-inferred July temperature reconstructions correspond well with the results of winter temperatures and precipitation derived from the pollen record using the Modern Analogue Technique (MAT). In the Allerød, the climate generally fluctuated between the phases of higher and lower continentality. The early Allerød in the Luciąża River valley is characterised by relatively cool summers and mild winters, with the trend of decreasing temperatures. Phase II started with high continentality reflected in the severe winters and relatively warm summers, as well as low precipitation sum. During the inter-Allerød oscillation, the temperatures of the coldest month and total annual precipitation reveal a distinct increase ca. 13,000 cal. BP (Fig. 11). This may suggest that the 'Gerzensee Oscillation' in central Poland was reflected not only in the lower summer temperatures but also in the drop of the climate continentality. Schenk et al. (2018, 2020) indicate that the high continentality index is the crucial aspect of the Younger Dryas climate. However, the warm summers in Rozprza during the stadial were not accompanied by cold and dry winters, but quite opposite – pollen-inferred temperatures of the coldest month are mild and stable (ca. −6 °C), while humidity was initially high, and only later decreased (Fig. 11). The temperature change between the Allerød and Younger Dryas was lower in the central-eastern part of Europe (Birks and Birks, 2014; Brooks and Langdon, 2014; Kubovčík et al., 2021). Mild climate records in the Rozprza site are generally consistent with the chironomid-inferred temperature trends for GI-1a/GS-1 transition in northwest Europe, showing a decreasing gradient of temperatures to the south (Brooks and Langdon, 2014). Consequently, the cold event of Younger Dryas was less distinct in the Rozprza site, localised nearly 100 km south of Gościąż lake.

6. Conclusion

Our results prove that the meandering system developed in Luciąża valley close to Rozprza as early as in the Oldest Dryas or not later than in Bølling, earlier than proposed by Wachecka-Kotkowska (2004) for Luciąża River. It is also one of the earliest meandering river patterns documented in central Poland. At the same time, there is no record of braided river patterns in Younger Dryas in the studied valley (see also Kittel et al., 2018a).

This research presents the first climatic reconstructions from the Allerød for central Poland performed with such high resolution. The results verify and complement the trend visible in other studies from the region and give one of the first well-documented records of the Gerzensee Oscillation from East-Central Europe supported by the chironomid analysis. The relatively warm Younger Dryas is to some extent consistent with the previous studies based on chironomid-inferred reconstructions. However, the pollen record also indicates mild winters, contradictory to Schenk et al. (2018, 2020). The local microclimatic conditions in small river valleys do not have to be in line with the general, global trends.

A comprehensive analysis of hydrogeological and morphological conditions determining the water cycle within the catchment area is a necessary but still often overlooked research stage in the reconstruction of morphodynamic processes and their impact on the climate change record. The composition of the applied methods, biotic record, geochemical and grain-size parameters against the background of the diversity of physico-geographical conditions and surface geology of the Luciąża river catchment turned out to be useful for the assessment of genesis and environment conditions of the Late Vistulian. The wide range of used proxies provided a possibly reliable picture of the past environment and its processes from a specific point in time and space.

Author contributions

OA-O: Conceptualization, Formal analysis, Investigation, Writing, Visualization; DO and DP: Writing, Formal analysis, Investigation, Visualization; BK, TL, OP, JS, and ES-K: Formal analysis; MK: Formal analysis, Writing; RS-R and AW: Investigation, Visualization, Writing; MP: Writing – Review & Editing, Supervision; PK: Conceptualization, Investigation, Writing, Supervision, Project administration.

Data availability

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ammann, B., Birks, H.J.B., Brooks, S.J., Eicher, U., von Grafenstein, U., Hofmann, W., Lemdahl, G., Schwander, J., Tobolski, K., Wick, L., 2000. Quantification of biotic responses to rapid climatic changes around the Younger Dryas - a synthesis. Palaeogeogr. Palaeoclimatol. Palaeoecol. 159, 313–347.

Ammann, B., van Leeuwen, F.N., van der Knap, W.O., Lischke, H., Heiri, O., Tinner, W., 2013. Vegetation response to rapid Warming and to minor climatic fluctuations during the Late-Glacial Interstadial (GI-1) at Gerzensee (Switzerland). Palaeogeogr. Palaeoclimatol. Palaeoecol. 391, 40e59.

Andersen, T., Cranston, P.S., Epler, J.H., 2013. In: Chironomidae of the Holarctic region: keys and diagnoses. Part 1. Larvae. Insect Systematics and Evolution Supplements, 66. Scandinavian Entomology, Lund.

Andres, W., Bos, J.A.A., Houben, P., Kalis, A.J., Nolte, S., Rittweger, H., Wunderlich, J., 2001. Environmental change and fluvial activity during the Younger Dryas in central Germany. Quat. Int. 79, 89–100.

Balwierz, Z., 2010. Analiza pyłkowa osadów torfowiska Żabieniec. In: Twardy, J., Żurek, S., Forysiak, J. (Eds.), Torfowisko Żabieniec. Warunki naturalne, rozwój i zapis zmian paleoekologicznych w jego osadach. Bogucki Wyd. Nauk., Poznań, pp. 179–188.

Balwierz, Z., 2011. Analiza palinologiczna osadów organogenicznych w Aleksandrowie Łódzkim. In: Niesiołowska-Śreniowska, E., Płaza, D.K., Marosik, P., Balwierz, Z. (Eds.), Obozowiska ze starszej i środkowej epoki kamienia na stanowisku w Aleksandrowie Łódzkim w kontekście analizy środowiska. Muzeum Archeologiczne i Etnograficzne w Łodzi, Łódź, pp. 37–64.

Barczuk, A., Wachecka-Kotkowska, L., 2015. Analysis of heavy minerals as a method for determining the source of the glaciofluvial sediments in the Piotrków Trybunalski, Radomsko and Przedbórz area (Central Poland). Acta Geogr. Lodz. 103, 9–24.

Berggren, G., 1981. Atlas of Seeds and Small Fruits of Northwest-European Plant Species with Morphological Descriptions: Cyperaceae. Statens naturvetenskapliga forskningsråd (distr.), Stockholm.

Berglund, B.E., Ralska-Jasiewiczowa, M., 1986. Pollen analysis and pollen diagrams. In: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. Wiley and Sons Ltd., Chichester, pp. 455–484.

Beug, H.-J., 2004. Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Verlag Dr. Friedrich Pfeil, München.

Biernat, B., 1994. Typical periods of floods occurrence. Table 32.3.6. In: Atlas of the Republic of Poland. Institute of Geography and Spatial Organization Polish Academy of Science, Warsaw.

Birks, H.H., Ammann, B., 2000. Two terrestrial records of rapid climatic change during the glacial-Holocene transition (14,000–9,000 calendar years B.P.) from Europe. Proc. Natl. Acad. Sci. U.S.A. 97, 1390–1394.

Birks, H.H., Birks, H.J.B., 2014. To what extent did changes in July temperature influence late-glacial vegetation patterns in NW Europe? Quat. Sci. Rev. 106, 262–277.

Birks, H.H., Battarbee, R.W., Birks, H.J.B., 2000. The development of the aquatic ecosystem at Kråkenes Lake, western Norway, during the late-glacial and early-Holocene – a synthesis. J. Paleolimnol. 23, 91–114.

Birks, H.J.B., Heiri, O., Seppä, H., Bjune, A.E., 2010. Strengths and weaknesses of quantitative climate reconstructions based on late-Quaternary biological proxies. Open Ecol. J. 3, 68–110.

Bitušík, P., Hamerlík, L., 2014. Identification guide of Slovakian chironomid larvae (Diptera: Chironomidae). Part II. Tanypodinae. Belianum. Vydavat. Univ. Matej Bela v Banskej Bystrici, Fakulta prírodných vied.

Bjerring, R., Becares, E., Declerck, S., Gross, E.M., Hansson, L.-A., Kairesalo, T., Nykänen, M., Halkiewicz, A., Kornijów, R., Conde-Porcuna, J.M., Seferlis, M., Noges, T., Moss, B., Amsinck, S.L., Vad Odgaard, B., Jeppesen, E., 2009. Subfossil Cladocera in relation to contemporary environmental variables in 54 Pan-European lakes. Freshw. Biol. 54, 2401–2417.

Bohncke, S., Vandenberghe, J., Huijzer, A.S., 1993. Periglacial environments during the Weichselian late glacial in the Maas valley, The Netherlands. Geol. Mijnbouw 72, 193–210.

Borisova, O., Sidorchuk, A., Panin, A., 2006. Palaeohydrology of the Seim River basin, mid- Russian upland, based on palaeochannel morphology and palynological data. Catena 66, 53–73.

Borówka, R.K., 1992. The Pattern and Magnitude of Denudation in Intraplateau Sedimentary Basins during the Late Vistulian and Holocene. Seria Geografia vol. 54. Wyd. UAM, Poznań.

Borówka, R.K., Tomkowiak, J., Okupny, D., Forysiak, J., 2015. Chemical composition of biogenic sediments from the River valley Luciąża (Bęczkowice peatland in the Piotrków Plain). Folia Quat. 83, 5–23.

Bronk Ramsey, C., 2008. Deposition models for chronological records. Quat. Sci. Rev. 27 (1–2), 42–60.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51 (1), 337–360.

Brooks, S.J., Birks, H.J.B., 2001. Chironomid-inferred air temperatures from Lateglacial and Holocene sites in north-west Europe: progress and problems. Quat. Sci. Rev. 20, 1723–1741.

Brooks, S.J., Langdon, P.G., 2014. Summer temperature gradients in northwest Europe during the Lateglacial to early Holocene transition (15-8 ka BP) inferred from chironomid assemblages. Quat. Int. 341, 80–90.

Brooks, S.J., Langdon, P.G., Heiri, O., 2007. The Identification and Use of Palaearctic Chironomidae Larvae in Palaeoecology. QRA Technical Guide No. 10. Quaternary Research Association, London.

Cappers, R.T.J., Bekker, R.M., Jans, J.E.A., 2006. Digital Seed Atlas of the Netherlands. Groningen University Library, Groningen, Barkhuis.

Carlson, A.E., 2010. What caused the younger Dryas cold event? Geology 38 (4), 383–384. https://doi.org/10.1130/focus042010.1.

Cherkinsky, A., Culp, R.A., Dvoracek, D.K., Noakes, J.E., 2010. Status of the AMS facility at the University of Georgia. Nucl. Instrum. Methods Phys. Res. B 268 (7–8), 867–870.

Climate-Data.org. www.climate-data.org (Accessed 2 Mar 2021).

De Klerk, P., 2002. Changing vegetation patterns in the Endinger Bruch area (Vorpommern, NE Germany) during the Weichselian lateglacial and early Holocene. Rev. Palaeobot. Palynol. 119, 275–309.

Dempster, M., Dunlop, P., Scheib, A., Cooper, M., 2012. Principal component analysis of the geochemistry of soil developed on till in Northern Ireland. J. Maps 9 (3), 373–389.

Dzieduszyńska, D.A., 2011. Younger Dryas cooling and its morphogenetic importance in the Łódź region (Central Poland). Acta Geogr. Lodz. 98, 101. Łódzkie Towarzystwo Naukowe, Łódź.

Dzieduszyńska, D.A., 2019. Timing of environmental changes of the Weichselian decline (18.0–11.5 ka cal BP) using frequency distribution of 14C dates for the Łódź region, Central Poland. Quat. Int. 501, 135–146.

Dzieduszyńska, D.A., Forysiak, J., 2019. Chronostratigraphy of the late Vistulian in central Poland and the correlation with Vistulian glacial phases. Stud. Quat. 36 (2), 137–145.

Dzieduszyńska, D.A., Kittel, P., Petera-Zganiacz, J., Brooks, S.J., Korzeń, K., Krąpiec, M., Pawłowski, D., Płaza, D.K., Płóciennik, M., Stachowicz-Rybka, R., Twardy, J., 2014. Environmental influence on forest development and decline in the Warta River valley (Central Poland) during the Late Weichselian. Quat. Int. 324, 99–114. https://doi.org/10.1016/j.quaint.2013.07.017.

Dzieduszyńska, D.A., Petera-Zganiacz, J., Roman, M., 2020. Vistulian periglacial and glacial environments in central Poland: an overview. Geol. Q. 64 (1), 54–73.

Feurdean, A., Perşoiu, A., Tanţău, I., Stevens, I., Magyari, E.K., Onac, B.P., Marković, S., Andrič, M., Connor, S., Fărcaş, S., Gałka, M., Gaudeny, T., Hoek, W., Kołaczek, P., Kuneš, P., Lamentowicz, M., Marinova, E., Michczyńska, D.J., Perşoiu, I., Płóciennik, M., Słowiński, M., Stancikaite, M., Sumegi, P., Svensson, A., Tămaş, T., Timar, A., Tonkov, S., Toth, M., Veski, S., Willis, K.J., Zernitskaya, V., 2014. Climate variability and associated vegetation response throughout Central and Eastern Europe (CEE) between 60 and 8 ka. Quat. Sci. Rev. 106, 206–224. https://doi.org/10.1016/j.quascirev.2014.06.003.

Folk, R., Ward, W., 1957. Brazos River bar: a study in the significance of grain size parameters. J. Sediment. Petrol. 27 (1), 3–26.

Forysiak, J., 2012. Record of changes in the natural environment of the Late Weichselian and Holocene preserved in the sediments of peatlands of the Łódź Region. Acta Geogr. Lodz. 90, 1–116.

Forysiak, J., 2015. Geomorphological diversity of peatland basins in the Łódź region and its significance for the accumulation of biogenic sediments, Bulletin of Geography. Phys. Geogr. 8 (1), 59–70.

Forysiak, J., Obremska, M., Pawłowski, D., Kittel, P., 2010. Late Vistulian and Holocene changes in the Ner river valley in light of geological and palaeoecological data from the Ner-Zawada peatland. Geologija 52, 25–33.

Frey, D.G., 1986. Cladocera analysis. In: Berglund, B.E. (Ed.), Handbook of Holocene paleoecology and paleohydrology. John Wiley and Sons, Chichester, pp. 667–692.

Gałka, M., Lewandowska, A., Niedzielski, P., Sim, T.G., Swindles, G.T., Szczurek, G., 2020. Late Glacial and early Holocene development of an oxbow lake in Central Europe (Poland) based on plant macrofossil and geochemical data. Holocene 30 (1), 178–189.

Gao, C., Boreham, S., Preece, R.C., Gibbard, P.L., Briant, R.M., 2007. Fluvial response to rapid climate change during the devensian (Weichselian) lateglacial in the river Great Ouse, S England, UK. Sediment. Geol. 202, 193–210.

Goslar, T., Bałaga, K., Arnold, M., Tisnerat, N., Starnawska, E., Kuźniarski, M., Chróst, L., Walanus, A., Więckowski, K., 1999. Climate-related variations in the composition of the late glacial and early Holocene sediments of Lake Perespilno (eastern Poland). Quat. Sci. Rev. 18, 899–911.

Goździk, J., Konecka-Betley, K., 1992. Late-Vistulian carbonateous formations in outflow-closed depressions of the Bełchatow brown coal strip mine. Part II. Chemical and mineral composition. Soil Sci. Ann. 43 (3/4), 113–124.

Guiot, J., 1990. Methodology of the last climatic cycle reconstruction in France from pollen data. Palaeogeogr. Palaeoclimatol. Palaeoecol. 80, 49–69.

Hoffmann, T., Lang, A., Dikau, R., 2008. Holocene river activity: analysing 14C-dated fluvial and colluvial sediments from Germany. Quat. Sci. Rev. 27, 2031–2040.

Howard, L.C., Wood, P.J., Greenwood, M.T., Rendell, H.M., Brooks, S.J., Armitage, P.D., Extence, C.A., 2010. Subfossil Chironomidae as indicators of palaeoflow regimes: integration into the PalaeoLIFE flow index. J. Quat. Sci. 25, 1270–1283.

Huntley, B., Birks, H.J.B., 1983. An Atlas of Past and Present Pollen Maps for Europe, 0-13,000 Years Ago. Cambridge University Press, Cambridge.

Hydroportal, 2015. www.isok.gov.pl/hydroportal.html (Accessed 4 Feb 2021).

Jakiel, A., 2013. Reconstruction of Palaeoenvironmental Changes of a Lowland Bog Based on the Analysis of Chironomid Assemblages.. Master's thesis. University of Lodz, Łódź.

Jokiel, P., 2015. Metody statystyczne w analizach hydrologicznych środkowej Polski. Wyd. Nauk. UŁ, Łódź, p. 294.

Jokiel, P., 2016. Seasonality to river outflow in Central Poland and its variability over a multiannual period period revealed by mass diagram curves and half-outflow terms. Przegląd Geogr. 88 (1), 53–74.

Jokiel, P., Stanisławczyk, B., 2016. Long-term changes and variability in the seasonality of river discharge for selected Polish rivers. Prace Geograficzne IGiGP UJ 144, 9–33.

Jokiel, P., Tomalski, P., 2015. Hydrological seasons in the rivers of central Poland. Przegląd Geogr. 87 (1), 71–93.

Juggins, S., 2007. C2 Version 1.5 User Guide. Software for Ecological and Palaeoecological Data Analysis and Visualisation. Newcastle University, Newcastle upon Tyne.

Juggins, S., 2017. rioja: Analysis of Quaternary Science Data. R package version 0.9-21. http://cran.r-project.org/package=rioja.

Kaiser, K., Barthelmes, A., Czakó Pap, S., Hilgers, A., Janke, W., Kuhn, P., Theuerkauf, M., 2006. A lateglacial palaeosol cover in the Altdarss area, southern Baltic Sea coast (northeast Germany): investigations on pedology, geochronology and botany. Netherlands J. Geosci. - Geologie en Mijnbouw 85 (3), 197–220.

Kaiser, K., Lorenz, S., Germer, S., Juschus, O., Küster, M., Libra, J., Bens, O., Hütti, R.F., 2012. Late Quaternary evolution of rivers, lakes and peatlands in northeast Germany reflecting past climates and human impact – an overview. E&G Quater. Sci. J. 61, 103–132.

Kats, N.Ya, Kats, S.V., Kipiani, M.G., 1965. Atlas I Opredelitel' Plodov I Semyan Vstrechayushchikhsya V Chetviertichnykh Otlozheniyach SSSR (Atlas and Keys of Fruits and Seeds Occurring in the Quaternary Deposits of the USSR). Izdat. Nauka, Moskva.

Kittel, P., 2015. The alternative interpretation of chronology of flood events in the mid-Warta River valley: record of Early Holocene alluviation in the Koło Basin (central Poland). Quat. Int. 386, 116–121.

Kittel, P., Sikora, J., Wroniecki, P., 2015. The morphology of the Luciąża River valley floor in the vicinity of the Rozprza medieval ring-fort in light of geophysical survey. Bulletin of Geography. Phys. Geogr. 8, 95–106.

Kittel, P., Płóciennik, M., Borówka, R.K., Okupny, D., Pawłowski, D., Peyron, O., Stachowicz-Rybka, R., Obremska, M., Cywa, K., 2016. Early Holocene hydrology and environments of the Ner River (Poland). Quat. Res. 85 (2), 187–203. https://doi.org/10.1016/j.yqres.2015.12.006.

Kittel, P., Sikora, J., Wroniecki, P., 2018a. A Late Medieval motte-and-bailey settlement in a lowland river valley landscape of Central Poland. Geoarchaeology 33 (5), 558–578.

Kittel, P., Sikora, J., Antczak, O., Brooks, S.J., Elias, S., Krąpiec, M., Luoto, T.P., Borówka, R.K., Okupny, D., Pawłowski, D., Płóciennik, M., Rzodkiewicz, M., Stachowicz-Rybka, R., Wacnik, A., 2018b. The palaeoecological development of the Late Medieval moat – multiproxy research at Rozprza, Central Poland. Quat. Int. 482, 131–156. https://doi.org/10.1016/j.quaint.2018.03.026.

Kotrys, B., Płóciennik, M., Sydor, P., Brooks, S.J., 2020. Expanding the Swiss-Norwegian chironomid training set with Polish data. Boreas 49, 89–107. https://doi.org/10.1111/bor.12406.

Kozarski, S., 1991. Warta: a case study of a lowland river. In: Starkel, L., Gregory, K.J., Thornes, J. (Eds.), Temperate Palaeohydrology. Wiley & Sons Ltd., Chichester, pp. 189–215.

Kołaczek, P., Gałka, M., Apolinarska, K., Gębica, P., Superson, S., Michno, A., Harmata, K., Szczepanek, K., Płóciennik, M., Gąsiorowski, M., Karpińska-Kołaczek, M., 2017. Lost in dating - problems with the absolute chronologies and sedimentation rates of Lake Glacial and Early Holocene oxbow lake deposits in Central Europe. Quat. Geochronol. 41, 187–201.

Krąpiec, M., Rakowski, A.Z., Huels, M., Wiktorowski, D., Hamann, C., 2018a. A new graphitization system for radiocarbon dating with AMS on the dendrochronological laboratory at AGH-UST Kraków. Radiocarbon 60 (4), 1091–1100.

Krąpiec, M., Michczyńska, D.J., Michczyński, A., Piotrowska, N., Goslar, T., Szychowska-Krąpiec, E., 2018b. Late glacial atmospheric radiocarbon variations recorded in Scots pine (*Pinus sylvestris* L.) wood from Kwiatków, Central Poland. Radiocarbon 60 (4), 1029–1040.

Krąpiec, M., Szychowska-Krąpiec, E., Barniak, J., Goslar Kittel, T.P., Michczyńska, D.J., Michczyński, A., Piotrowska, N., Rakowski, A., Wiktorowski, D., 2020. A tree-ring chronology from Allerød–YD transition from Koźmin (Central Poland). Geochronometria 47 (1), 101–111.

Kubovčík, V., Hošek, J., Heiri, O., Rojik, F., Vaterková, S., Trubač, J., Pokorný, P., 2021. Chironomid-based temperature and environmental reconstructions of the last glacial termination in southern Bohemia, Czech Republic. Palaeogeogr. Palaeoclimatol. Palaeoecol. 567, 110239. https://doi.org/10.1016/j.palaeo.2021.110239.

Lamentowicz, M., Kołaczek, P., Mauquoy, D., Kittel, P., Łokas, E., Słowiński, M., Jassey, V.E.J., Niedziółka, K., Kajukało-Drygalska, K., Marcisz, K., 2019. Always on the tipping point – a search for signals of past societies and related peatland ecosystem critical transitions during the last 6500 years in N Poland. Quat. Sci. Rev. 225, 105954.

Latałowa, M., Borówka, R.K., 2006. The Allerød/Younger Dryas transition in Wolin Island, northwest Poland, as reflected by pollen, macrofossils, and chemical content of an organic layer separating two aeolian series. Veg. Hist. Archaeobotany 15, 321–331.

Lohne, Ø.S., Mangerud, J., Birks, H.H., 2013. Precise 14C ages of the Vedde and Saksunarvatn ashes and the Younger Dryas boundaries from western Norway and their comparison with the Greenland Ice Core (GICC05) chronology. J. Quat. Sci. 28, 490–500.

Luoto, T.P., 2009. An assessment of lentic ceratopogonids, ephemeropterans, trichopterans and oribatid mites as indicators of past environmental change in Finland. Ann. Zool. Fenn. 46, 259–270.

Luoto, T.P., Kotrys, B., Płóciennik, M., 2019. East European chironomid-based calibration model for past summer temperature reconstructions. Clim. Res. 77, 63–76. https://doi.org/10.3354/cr01543.

Makohonienko, M., Gaillard, M.-J., Tobolski, K., 1998. Modern pollen/land-use relationships in ancient cultural landscapes of north-western Poland, with an emphasis on mowing, grazing, and crop cultivation. In: Gaillard, M.-J., Berglund, B. E. (Eds.), Quantification of Land Surfaces Cleared of Forests during the Holocene – Modern Pollen/Vegetation/Landscape Relationships as an Aid to the Interpretation of Fossil Pollen Sata. Gustav Fischer Verlag, Stuttgart, pp. 85–98.

Mangerud, J., 2021. The discovery of the Younger Dryas, and comments on the current meaning and usage of the term. Boreas 50 (1), 1–5. https://doi.org/10.1111/bor.12481.

Manikowska, B., 1982. Fossil soils in dunes of Central Poland. Soil Sci. Ann. 33 (3/4), 119–133.

Manikowska, B., 1997. Periglacial cover sediments and soil profile evolution on the fluvioglacial interfluve area of Central Poland. Soil Sci. Ann. 48 (3/4), 151–167.

Manikowska, B., 1999. Fossil soils and pedogenetic periods in the evolution of central Poland environment after the Wartian Glaciation. Acta Geogr. Lodz. 76, 41–100.

Mann, M.E., 2002. The value of multiple proxies. Science 297, 1481–1482.

Marks, L., 2011. Quaternary Glaciations in Poland. In: Ehlers, J., Gibbard, P.L., Hughes, P.D. (Eds.), Quaternary Glaciations—Extent and Chronology—A Closer Look. Developments in Quaternary Sciences, vol. 15. Elsevier, Amsterdam, pp. 299–303.

Marosik, P., Forysiak, J., 2014. Ukształtowanie terenu, budowa geologiczna i rozwój paleogeograficzny otoczenia grodziska w Tumie. In: Grygiel, R., Jurek, T. (Eds.), Początki Łęczycy. Archeologia środowiskowa średniowiecznej Łęczycy. Muzeum Archeologiczne i Etnograficzne w Łodzi, Łódź, pp. 59–94.

Meteomodel.pl, 2019. Historical measurement data (Historyczne dane pomiarowe). https://meteomodel.pl/dane/historyczne-dane-pomiarowe/ (Accessed 4 Feb 2021).

Moller Pillot, H.K.M., 2009. Chironomidae Larvae. Biology and Ecology of the Chironomini. KNNV Publishing, Zeist.

Moller Pillot, H.K.M., 2013. Chironomidae Larvae of the Netherlands and Adjacent Lowlands, Biology and Ecology of the Aquatic Orthocladiinae, Prodiamesinae, Diamesinae, Buchonomyiinae, Podonominae, Telmatogetoninae. KNNV Publishing, Zeist.

Müller, D., Tjallingii, R., Płóciennik, M., Luoto, T.P., Kotrys, B., Plessen, B., Ramisch, A., Schwab, M.J., Błaszkiewicz, M., Słowiński, M., Brauer, A., 2021. New insights into lake responses to rapid climate change: the Younger Dryas in Lake Gościąż, central Poland. Boreas 50 (2), 535–555. https://doi.org/10.1111/bor.12499.

Nadeau, M.-J., Grootes, P.M., Schleicher, M., Hasselberg, P., Rieck, A., Bitteling, M., 1998. Sample throughput and data quality at the Leibniz-Labor AMS facility. Radiocarbon 40 (1), 239–245.

Nalepka, D., Walanus, A., 2003. Data processing in pollen analysis. Acta Palaeobot. 43 (1), 125–134. http://www.adamwalanus.pl/Polpal.html.

Nazarova, L.B., Self, A.E., Brooks, S.J., Solovieva, N., Syrykh, L.S., Dauvalter, V.A., 2017. Chironomid fauna of the lakes from the Pechora River Basin (East of European part of Russian Arctic): ecology and reconstruction of recent ecological changes in the region. Contemp. Probl. Ecol. 10, 350–362.

Nevalainen, L., 2011. Intra-lake heterogeneity of sedimentary cladoceran (Crustacea) assemblages forced by local hydrology. Hydrobiologia 676, 9–22.

Niska, M., Jonczak, J., Gadziszewska, J., 2017. Late Pleistocene and Holocene environmental evolution of the Wkra river valley near Bielawy Gołuskie (central Poland) recorded in palaeo-oxbow lake deposits. Geol. Q. 61 (2), 305–318.

Obreht, I., Wormer, L., Brauer, A., Wendt, J., Alfken, S., De Vleeschouwer, D., Elvert, M., Hinrichs, K.-U., 2020. An annually resolved record of Western European vegetation response to Younger Dryas cooling. Quat. Sci. Rev. 231, 106198.

Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., Wagner, H., 2019. vegan: Community Ecology Package. R package version 2.5-6. https://CRAN.R-project.org/package=vegan.

Okupny, D., Pawłowski, D., 2021. Elemental composition of biogenic sediments reveals palaeoclimatic changes during the Late Weichselian in a Central European river valley: a statistical approach. Catena 200, 105188. https://doi.org/10.1016/j.catena.2021.105188.

Okupny, D., Malkiewicz, M., Pawłowski, D., Ludwikowska-Kędzia, M., Borówka, R.K., Forysiak, J., Michczyński, A., Jucha, W., Cybul, P., Żurek, P., 2019. Late Glacial palaeoenvironmental changes in the southern part of the Holy Cross Mountains based on the "Białe Ługi" peatland record. Stud. Quat. 36 (2), 119–135.

Okupny, D., Borówka, R.K., Cedro, B., Sławińska, J., Tomkowiak, J., Michczyński, A., Kozłowska, D., Kowalski, K., Siedlik, K., 2020. Geochemistry of a sedimentary section at the Wąwelnica archaeological site, Szczecin Hills (western Pomerania). Acta Geogr. Lodz. 110, 169–186.

Oświt, J., Żurek, S., Liwski, S., 1980. Soil condition in the Ślina river valley against the background of water conditions. Zesz. Probl. Postępów Nauk. Rol. 234, 159–194.

Pawłowski, D., 2012. Younger Dryas Cladocera assemblages from two valley mires in central Poland and their potential significance for climate reconstructions. Geologos 18, 237–249. https://doi.org/10.2478/v10118-012-0012-2.

Pawłowski, D., 2017. The usefulness of subfossil Cladocera remains in Younger Dryas climatic reconstructions in central Poland. Acta Geol. Pol. 67, 567–584. https://doi.org/10.1515/agp-2017-0026.

Pawłowski, D., Kowalewski, G., Milecka, K., Płóciennik, M., Woszczyk, M., Zieliński, T., Okupny, D., Włodarski, W., Forysiak, J., 2015a. A reconstruction of the palaeohydrological conditions of a floodplain: a multi-proxy study from the Grabia River valley mire, central Poland. Boreas 44, 543–562. https://doi.org/10.1111/bor.12115.

Pawłowski, D., Płóciennik, M., Brooks, S.J., Luoto, T.P., Milecka, K., Nevalainen, L., Peyron, O., Self, A., Zieliński, T., 2015b. A multiproxy study of Younger Dryas and Early Holocene climatic conditions from the Grabia River palaeo-oxbow lake (central Poland). Palaeogeogr. Palaeoclimatol. Palaeoecol. 438, 34–50. https://doi.org/10.1016/j.palaeo.2015.07.031.

Pawłowski, D., Borówka, R.K., Kowalewski, G., Luoto, T.P., Milecka, K., Nevalainen, L., Okupny, D., Płóciennik, M., Woszczyk, M., Zieliński, T., Tomkowiak, J., 2016. The response of flood-plain ecosystems to the Late Glacial and Early Holocene hydrological changes: a case study from a small Central European river valley. Catena 147, 411–428. https://doi.org/10.1016/j.catena.2016.07.034.

Petera-Zganiacz, J., Dzieduszyńska, D.A., Twardy, J., Pawłowski, D., Płóciennik, M., Lutyńska, M., Kittel, P., 2015. Younger Dryas flood events: a case study from the middle Warta River valley (Central Poland). Quat. Int. 386, 55–69. https://doi.org/10.1016/j.quaint.2014.09.074.

Pleskot, K., Apolinarska, K., Kołaczek, P., Suchora, M., Fojutowski, M., Joniak, T., Kotrys, B., Kramkowski, M., Słowiński, M., Woźniak, M., Lamentowicz, M., 2020. Searching for the 4.2 ka climate event at Lake Spore, Poland. Catena 191, 104565.

Płóciennik, M., Self, A., Birks, H.J.B., Brooks, S.J., 2011. Chironomidae (Insecta: Diptera) succession in Żabieniec bog and its palaeo-lake (central Poland) through the late Weichselian and Holocene. Palaeogeogr. Palaeoclimatol. Palaeoecol. 307, 150–167. https://doi.org/10.1016/j.palaeo.2011.05.010.

Płóciennik, M., Kittel, P., Borówka, R.K., Cywa, K., Okupny, D., Obremska, M., Pawłowski, D., Stachowicz-Rybka, R., Szperna, R., Witkowski, A., 2016. Warunki paleoekologiczne subkopalnego koryta Kolonia Bechcice na tle hydrologii środkowego odcinka doliny Neru. Acta Geogr. Lodz. 105, 107–124.

Płóciennik, M., Pawłowski, D., Vilizzi, L., Antczak-Orlewska, O., 2020. From oxbow to mire: Chironomidae and Cladocera as habitat palaeoindicators. Hydrobiologia 847, 3257–3275. https://doi.org/10.1007/s10750-020-04327-6.

R Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Austria.

Ralska-Jasiewiczowa, M., 2004. Early Holocene. In: Ralska-Jasiewiczowa, M., Latałowa, M., Wasylikowa, K., Tobolski, K., Madeyska, E., Wright, H.E., Turner, C. (Eds.), Late Glacial and Holocene History of Vegetation in Poland Based on Isopollen Maps. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, pp. 393–397.

Ralska-Jasiewiczowa, M., Goslar, T., Różanski, K., Wacnik, A., Czernik, J., Chrost, L., 2003. Very fast environmental changes at the Pleistocene/Holocene boundary, recorded in laminated sediments of Lake Gościąż, Poland. Palaeogeogr. Palaeoclimatol. Palaeoecol. 193, 225–247.

Rasmussen, S.O., Bigler, M., Blockey, S.P., Blunier, T., Buchardt, S.L., Clausen, H.B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S.J., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W., Lowe, J.J., Pedro, J.B., Popp, T., Seierstad, I.K., Steffensen, J.P., Svensson, A.M., Vallelonga, P., Vinther, B., Walker, M.J., Wheatley, J.J., Winstrup, M., 2014. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. Quat. Sci. Rev. 106, 14e28.

Reille, M., 1998. Pollen et Spores d'Europe et d'Afrique du Nord. Supplement 2. In: Pollen et Spores d'Europe. Laboratoire de Botanique historique et Palynologie, Marseille.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C. E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and Marine 13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55 (4), 1869–1887.

Reimer, P., Austin, W., Bard, E., Bayliss, A., Blackwell, P., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R., Friedrich, M., Grootes, P., Guilderson, T., Hajdas, I., Heaton, T., Hogg, A., Hughen, K., Kromer, B., Manning, S., Muscheler, R., Palmer, J., Pearson, C., van der Plicht, J., Reimer, R., Richards, D., Scott, E., Southon, J., Turney, C., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S., 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62 (4), 725–757. https://doi.org/10.1017/RDC.2020.41.

Robertson, A.L., 1990. The population dynamics of Chydoridae and Macrothricidae (Cladocera:Crustacea) from the river Thames, U.K. Freshw. Biol. 24, 375–389.

Rolland, N., Larocque, I., 2007. The efficiency of kerosene flotation for extraction of chironomid head capsules from lake sediments samples. J. Paleolimnol. 37, 565–572.

Rotnicki, K., 1988. Main phases of erosion and accumulation in the Prosna valley in the last glacial-interglacial cycle. Geogr. Pol. 53, 53–66.

Schenk, F., Väliranta, M., Muschitiello, F., Tarasov, L., Heikkilä, M., Björck, S., Brandefelt, J., Johansson, A.V., Näslund, J.-O., Wohlfarth, B., 2018. Warm summers during the Younger Dryas cold reversal. Nat. Commun. 9, 1634.

Schenk, F., Bennike, O., Väliranta, M., Avery, R., Björck, S., Wohlfarth, B., 2020. Floral evidence for high summer temperatures in southern Scandinavia during 15–11 cal ka BP. Quat. Sci. Rev. 233, 106243.

Schmid, P.E., 1993. A Key to the Larval Chironomidae and Their Instars from Austrian Danube Region Streams and Rivers with Particular Reference to a Numerical Taxonomic Approach. Part I. Diamesinae, Prodiamesinae and Orthocladiinae. Wass Abwass Suppl 3/93.

Schwander, J., Eicher, U., Amman, B., 2000. Oxygen isotopes of lake marl at Gerzensee and Leysin (Switzerland), covering the Younger Dryas and two minor oscillations, and their correlation to the GRIP ice core. Palaeogeogr. Palaeoclimatol. Palaeoecol. 159, 203e214.

Sikora, J., Kittel, P., Wroniecki, P., 2015a. Non-invasive research of the early-medieval strongholds in Central Poland and their settlement hinterland: Chełmo, Rękoraj, Rozprza, Stare Skoszewy, Szydłów (Nieinwazyjne badania grodzisk wczesnośredniowiecznych Polski Centralnej i ich zaplecza osadniczego: Chełmo, Rękoraj, Rozprza, Stare Skoszewy, Szydłów). Prace i Materiały Muzeum Archeologicznego i Etnograficznego w Łodzi. Seria Archeologiczna 46, 253–293.

Sikora, J., Kittel, P., Wroniecki, P., 2015b. From a point on the map to a shape in the landscape. Non-invasive verification of medieval ring-forts in Central Poland: Rozprza case study. Archaeologia Polona 53, 510–514.

Sikora, J., Kittel, P., Frączek, M., Głąb, Z., Golyeva, A., Mueller-Bieniek, A., Schneeweiss, J., Tomczyńska, Z., Wasylikowa, K., Wiedner, K., 2019. A palaeoenvironmental reconstruction of the rampart construction of the medieval ring-fort in Rozprza, Central Poland. Archaeol. Anthropol. Sci. 11 (8), 4187–4219.

Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), 2001a. Tracking Environmental Change Using Lake Sediments, Volume 3: Terrestrial, Algal, and Siliceous Indicators. Springer, Dordrecht.

Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), 2001b. Tracking Environmental Change Using Lake Sediments, Volume 4: Zoological Indicators. Springer, Dordrecht.

Stachowicz-Rybka, R., Korzeń, K., 2014. Rozwój roślinności w późnym vistulianie oraz funkcjonowanie i zanik ekosystemu leśnego w stanowisku Koźmin Las. Acta Geogr. Lodz. 102, 53–63.

Starkel, L., Michczyńska, J.D., Krąpiec, M., Margielewski, W., Nalepka, D., Pazdur, A., 2013. Progress in the Holocene chrono-climatostratigraphy of polish territory. Geochronometria 40, 1–21.

Stępień, E., Forysiak, J., 2017. Importance of geomorphological features for origin and the contemporary situation of selected peatlands in the middle Widawka river valley. Landform Anal. 34, 51–61.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen Spores 13, 615–621.

Święta-Musznicka, J., 2007. Palinologiczne spektra powierzchniowe osadów dennych trzech jezior w północnej Polsce. Stud. Lim. et Tel. 1 (2), 147–156.

Szczepanek, K., 1971. Kras staszowski w świetle badań paleobotanicznych. Acta Palaeobot. 12 (2), 63–140.

Szczepanek, K., 1982. Development of the peat-bog at Słopiec and the vegetational history of the Świętokrzyskie (Holy Cross) Mts. in the last 10 000 years. Acta Palaeobot. 22 (1), 117–130.

Szczepanek, K., Tobolski, K., Nalepka, D., 2004. *Alnus* Mill. — Alder. In: Ralska-Jasiewiczowa, M., Latałowa, M., Wasylikowa, K., Tobolski, K., Madeyska, E., Wright, H.E., Turner, Ch (Eds.), Late Glacial and Holocene History of Vegetation in Poland Based on isopollen Maps. W. Szafer Institute of Botany, Kraków, pp. 47–55.

Szeroczyńska, K., Sarmaja-Korjonen, K., 2007. Atlas of Subfossil Cladocera from Central and Northern Europe. Friends of Lower Vistula Society, Świecie.

Słowiński, M., Marcisz, K., Płóciennik, M., Obremska, M., Pawłowski, D., Okupny, D., Słowińska, S., Borówka, R., Kittel, P., Forysiak, J., Michczyńska, D.J., Lamentowicz, M., 2016. Drought as a stress driver of ecological changes in peatland – a palaeoecological study of peatland development between 3500 BCE and 200 BCE in central Poland. Palaeogeogr. Palaeoclimatol. Palaeoecol. 461, 272–291. https://doi.org/10.1016/j.palaeo.2016.08.038.

Słowiński, M., Zawiska, I., Ott, F., Noryśkiewicz, A.M., Plessen, B., Apolinarska, K., Rzodkiewicz, M., Michczyńska, D.J., Wulf, S., Skubała, P., Kordowski, J., Błaszkiewicz, M., Brauer, A., 2017. Differential proxy responses to late Allerød and early Younger Dryas climatic change recorded in varved sediments of the Trzechowskie palaeolake in Northern Poland. Quat. Sci. Rev. 158, 94–106. https://doi.org/10.1016/j.quascirev.2017.01.005.

Tolksdorf, J.F., Turner, F., Kaiser, K., Eckmeier, E., Bittmann, F., Veil, S., 2014. Potential of paleosols, sediments and archaeological features to reconstruct Late Glacial fire regimes in northern Central Europe – case study Grabow site and overview. Z. Geomorphol. 58 (1), 211–232.

Toonen, W.J., Munoz, S.E., Cohen, K.M., Macklin, M.G., 2020. High-resolution sedimentary paleoflood records in alluvial river environments: a review of recent methodological advances and application to flood hazard assessment. In: Herger, J., Fontana, A. (Eds.), Palaeohydrology. Traces, Tracks and Trails of Extreme Events. Springer, Switzerland, pp. 213–228.

Turkowska, K., 1988. Rozwój dolin rzecznych na Wyżynie Łódzkiej w późnym czwartorzędzie. Acta Geogr. Lodz. 57, 1–157.

Turkowska, K., 1990. Main fluvial episodes in the Ner Valley in the last 22 000 years; a detailed study in Lublinek near Łódź, Central Poland. Quat. Stud. Pol. 9, 85–99.

Turkowska, K., 2006. Geomorfologia Regionu Łódzkiego. Wydawnictwo Uniwersytetu Łódzkiego, Łódź.

Turkowska, K., Dzieduszyńska, D., 2011. Local evidence of landform evolution vs. global changes – a case of Younger Dryas study in the upper Ner Valley system, central Poland. Geogr. Pol. 84, 147–162.

Turner, F., Tolksdorf, J.F., Viehberg, F., Schwalb, A., Kaiser, K., Bittmann, F., von Bramann, U., Pott, R., Staesche, U., Breest, K., Veil, S., 2013. Lateglacial/early Holocene fluvial reactions of the Jeetzel river (Elbe valley, northern Germany) to abrupt climatic and environmental changes. Quat. Sci. Rev. 60, 91–109.

Vallenduuk, H.J., Moller Pillot, H.K.M., 2007. In: Chironomidae larvae of The Netherlands and Adjacent lowlands. General ecology and Tanypodinae. KNNV Publishing, Zeist.

Vandenberghe, J., Sidorchuk, A., 2020. Large palaeomeanders in Europe: distribution, formation process, age, environments and significance. In: Herget, J., Fontana, A. (Eds.), Palaeohydrology. Geography of the Physical Environment. Springer, Cham. https://doi.org/10.1007/978-3-030-23315-0_9.

Velichkevich, F.Yu, Zastawniak, E., 2006. Atlas of Pleistocene Vascular Plant Macroremains of Central and Eastern Europe, Part I – Pteridophytes and Monocotyledons. W. Szafer Institute of Botany, Polish Academy of Sciences, Krakow.

Velichkevich, F.Yu, Zastawniak, E., 2008. Atlas of Vascular Plant Macroremains from the Pleistocene of Central and Eastern Europe, Part II – Herbaceous Dicotyledons. W. Szafer Institute of Botany, Polish Academy of Sciences, Krakow.

Wachecka-Kotkowska, L., 2004. Ewolucja doliny Luciąży – uwarunkowania klimatyczne a lokalne. Acta Geogr. Lodz. 86, 1–161.

Walker, I.R., 2001. Midges: Chironomidae and related Diptera. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking environmental Change Using Lake sediments, Volume 4: Zoological Indicators. Kluwer Academic Press, Dordrecht, pp. 43–66.

Wasylikowa, K., 1964. Roślinność i klimat późnego glacjału w środkowej Polsce na podstawie badań w Witowie koło Łęczycy. Biul. Peryglac. 13, 261–417.

Wasylikowa, K., 2001. Przemiany roślinności jako odbicie procesów wydmotwórczych i osadniczych w młodszym dryasie i holocenie na stanowisku archeologicznym w Witowie koło Łęczycy. Prace i Materiały Muzeum Archeologicznego i Etnograficznego w Łodzi, Seria Archeologiczna 41, 43–79.

Wetzel, R.G., 1983. Limnology. Saunders College Publishing, Philadelphia.

Wicik, B., 2001. Iron accumulation in Narew river valley near Tykocin. Soil Sci. Ann. 52, 65–69.

Wierzbicki, G., Grygoruk, M., Grodzka-Łukaszewska, M., Bartold, P., Okruszko, T., 2020. Mire development and disappearance due to river capture as hydrogeological and geomorphological consequences of LGM ice-marginal valley evolution at the Vistula-Neman watershed. Geosciences 10 (9), 363.

Woszczyk, M., Cieśliński, R., Spychalski, W., 2009. Geochemistry of surface sediments of a coastal Lake Sarbsko (northern Poland). Stud. Quat. 26, 41–53.

Wójcicki, K., 2012. Stratigraphy of organic-rich deposits in floodplain environments: examples from the upper Odra river basin. Quaest. Geogr. 31 (3), 107–117.

Wu, B., Amelung, W., Xing, Y., Bol, R., Berns, A.E., 2019. Iron cycling and isotope fractionation in terrestrial ecosystems. Earth Sci. Rev. 190, 323–352.

Zarzycki, K., Trzcińska-Tacik, H., Różańska, W., Szeląg, W., Wołek, J., Korzeniak, U., 2002. Ecological Indicator Values of Vascular Plant of Poland. Biodiversity of Poland 2. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

Zawiska, I., Słowiński, M., Correa-Metrio, A., Obremska, M., Luoto, T., Nevalainen, L., Woszczyk, M., Milecka, K., 2015. The response of a shallow lake and its catchment to Late Glacial climate changes - a case study from eastern Poland. Catena 126, 1–10.

Zeeberg, J., 1998. The European sand belt in eastern Europe – and comparison of Late Glacial dune orientation with GCM simulation results. Boreas 27, 127–139.

Zwoliński, Z., 1985. Sedimentation vertical accretion of sediments on the Parsęta River floodplain. Badania Fizjograficzne nad Polską Zachodnią, Seria A, Geografia Fizyczna 35, 205–238.

Żurek, S., 1990. Interrelation between the peat-forming process and the elements of natural environment eastern Poland. Polish Agric. Ann. 220, 1–174.

Żurek, S., Okupny, D., 2015. Peatlands of the Łódź region. Studia Limnologica et Telmatologica 9 (2), 59–69.

Chapter III. Chironomidae assemblage sequence in the Holocene deposits of the Luciąża River palaeomeander

In the previous chapter, the palaeo-oxbow (RP W4 core) development during the Late Vistulian is described. The Holocene section of the RP W4 profile did not contain enough chironomid subfossil remains for palaeotemperature modelling but gives insight into the local habitat conditions and, indirectly, Luciąża fluvial activity from Atlantic up to Middle Ages.

The Holocene stratigraphy of RP W4 profile is based on four radiocarbon dates of bulk organic deposits (LSC technique) and two ^{14}C dates of selected terrestrial macrofossils (AMS technique). Both dating techniques are described in detail in Chapter V ('Methods' section). The coring site and methods are described in the 'Introduction' chapter. The lithology, organic matter content, and a cross-section of the studied palaeochannel fill (the southern wall of trench 4) are presented in Figure 4, Chapter II (Antczak-Orlewska *et al.*, 2021).

The studied Holocene sequence covers the period of the past ~9000 years. In Preboreal and Boreal, a hiatus in sedimentation took place between ca. 12,000 and 8700 cal. y BP, and later depositional gaps were registered between 3500 and 2000 cal. y BP based on a radiocarbon data set.

In the recorded Chironomidae sequence, four main phases can be distinguished. In the first stage, covering the Atlantic period (as indicated by ^{14}C dates) up to ca. 7.4 ky cal. BP (i.e. ~5400 BC), the midge larvae subfossils are recorded. The oxbow was then probably transforming into a shallow marsh or (back)swamp, which fed mostly with groundwater, as suggested by the subfossil dipteran record. The overall midge abundance was relatively low but still reaching in its peak 45 individuals per sample (2.37 head capsules per 1 cm^3 of sediment). Phytophilous chironomids, such as *Phaenopsectra* type A, *Ablabesmyia, Acricotopus* and *Corynoneura arctica*-type, indicate the presence of aquatic plants, probably not only rushes. *C. arctica*-type is often linked to cooler conditions, but it occurs in warmer lakes as well (Brooks *et al.*, 2007), so it cannot be treated here as a climatic indicator. The terrestrialisation process began at the end of Late Glacial (Chapter II) and continued during the Holocene, as suggested by a high share of hygropetric larvae (Fig. 3.1). These taxa live mostly in a range of telmatic habitats, such as a moist soil, splash zone, marshy water edges, moorland pools and bogs (Brooks *et al.*, 2007; Moller Pillot, 2013). Some of them (e.g. *Parametriocnemus-Paraphaenocladius* and *Krenopelopia*) are spring-dwellers (Cranston, 1982), indicating the presence of seepages within the studied backswamp. The hygropetric taxa often associated with oligotrophic conditions are accompanied in the bottom part of the sequence (early Atlantic) by *Polypedilum nubeculosum*-type and *Chironomus plumosus*-type, usually indicative to higher trophic state and muddy bottom, here inhabiting probably shallow puddles with poorly oxygenated water.

During most of the middle and late Holocene (from ca. 7.4 to ca. 2.0 ky cal. BP; 147-83 cm b.g.l.) no chironomid remains were recorded in the RP W4 core (Fig. 3.1). The interpretation of this fragment of sequence is difficult because of possible organic matter redeposition and, in consequence, inadequate dates. Nevertheless, a distinct decrease in the subfossil remains record is reported from the other proxies (Cladocera, diatoms, plant macrofossils) as well. Such a situation might be caused by unfavourable conditions for their preservation, such as drying and rotting of organic deposits. The sedentation of peat (Fig. 3.1) indicates the paludification of the studied oxbow.

The chironomid assemblages reappeared in the Early Medieval Period (from ca. 600 AD), besides one *C. plumosus*-type head capsule recorded in the sample estimated at the Roman period (Fig. 3.1). The reappearance of midge larvae might be associated with the possible increase of flooding activity in the Luciąża River valley, as indicated by the presence of rheophilic *Rheocricotopus effusus*-type. It was accompanied by *Micropsectra insignilobus*-type, a morphotype including several rheophilic and cold-adapted species, which coincides with the climate cooling in Europe (Büntgen *et al.*, 2011). *Chironomus plumosus*-type, *Microtendipes pedellus*-type and *Psectrocladius limbatellus*-type are common taxa, often occurring in moorland pools and temporary water bodies, as backswamps. Here they were developing most probably in the shallow periodic puddles of water. The second episode of the increased flood activity took place later in the Middle Ages (from ca. 9th up to 11th century AD; 60-55 cm b.g.l.). Similar events were also noted elsewhere in East-Central Europe (e.g. Schneeweiss & Schatz, 2014). The backswamp could have then suitable habitats for development of typically rheophilic taxa (e.g. *Diamesa*, Simuliidae, *Polypedilum convictum*-type) or they might be washed from the swollen river together with overbank sediments. Besides rheophiles, also some eurytopic chironomids often inhabiting fluvial habitats (e.g. *Paratendipes albimanus*-type, *Micropsectra contracta*-type) were recorded. They co-occurred with hygropetric midges, such as *Krenopelopia* and *Natarsia*, which indicate the possible presence of seepages (Fig. 3.1). In this case, the main driver in shaping midge communities was not climate, but rather the hydrological conditions. Increased chironomid abundance (though still low, <1.5 head capsule/1 cm^3) and higher richness of phytophilous taxa (some of them associated with rather high water trophic state, like *Cricotopus intersectus*-type and *Polypedilum nubifer*-type) indicate more stable water conditions, and not only short-lasting episodes of inundation. This phase ended ca. 13th-14th century AD with the deposition of the upper unit of overbank deposits. In the studied sequence, no Chironomidae are recorded during the Late Medieval and Early Modern periods (up to ca. 1600 AD), described in Chapters IV (Kittel *et al.*, 2018) and V (Antczak-Orlewska *et al.*, 2021).

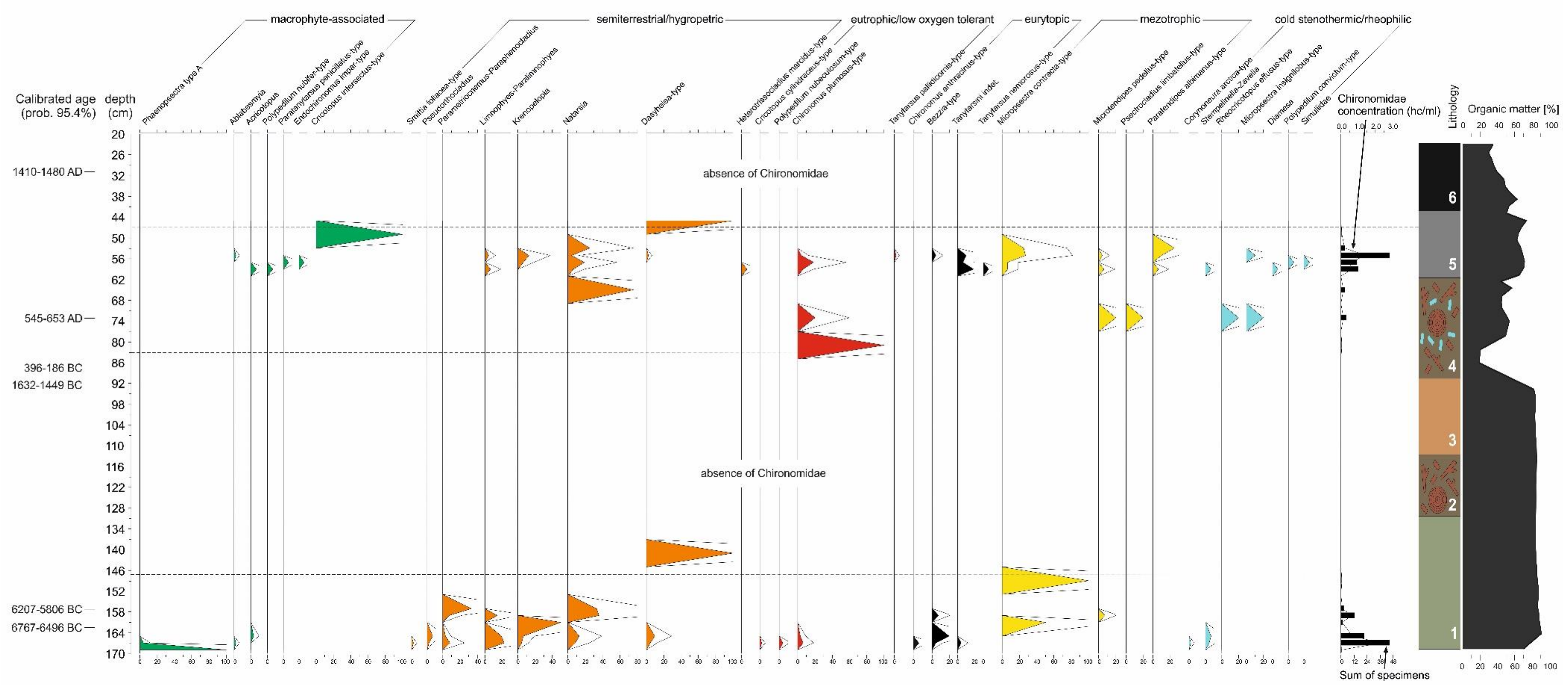

Fig. 3.1. Percentage stratigraphic diagram for the Holocene part of the RP W4 profile, presenting recorded Chironomidae, Ceratopogonidae and Simuliidae taxa, grouped according to ecological preferences. Lithology: 1 – coarse detritus gyttja with try branches, 2 – peat with wood fragments, 3 – peat penetrated by present-day try roots, 4 – peaty organic mud with wood fragments and vivianite, 5 – overbank organic mud with plant detritus, 6 – overbank organic mud with charcoal.

References

Antczak-Orlewska O., Okupny D., Pawłowski D., Kotrys B., Krąpiec M., Luoto T.P., Peyron O., Płóciennik M., Stachowicz-Rybka R., Wacnik A., Szmańda J.B., Szychowska-Krąpiec E., Kittel P. 2021. The environmental history of the oxbow in the Luciąża River valley – Study on the specific microclimate during Allerød and Younger Dryas in central Poland. *Quaternary International*, in press.

Brooks S. J., Langdon P. G., Heiri O. 2007. The identification and use of Palaearctic Chironomidae larvae in palaeoecology. Quaternary Research Association Technical Guide 10.

Büntgen U., Tegel W., Nicolussi K., McCormick M., Frank D., Trouet V., Kaplan J.O., Herzig F., Heussner K.U., Wanner H., Luterbacher J., Esper J. 2011. 2500 years of European climate variability and human susceptibility. Science 331, 578–582.

Cranston P. S. 1982. A key to the larvae of the British Orthocladiinae (Chironomidae). Freshwater Biological Association Scientific Publication No. 45.

Kittel P., Sikora J., Antczak, O., Brooks S.J., Elias S.A., Krąpiec M., Luoto T.P., Okupny D., Pawłowski D., Płóciennik M., Rzodkiewicz M., Stachowicz-Rybka R., Wacnik A. 2018. The palaeoecological development of the Late Medieval moat – Multiproxy research at Rozprza, Central Poland. Quaternary International 482, 131–156.

Moller Pillot H. K. M. 2013. Chironomidae larvae of the Netherlands and adjacent lowlands, Biology and Ecology of the aquatic Orthocladiinae, Prodiamesinae, Diamesinae, Buchonomyiinae, Podonominae, Telmatogetoninae. KNNV Publishing, Zeist.

Schneeweiss J., Schatz T. 2014. The impact of landscape change on the significance of political centres along the lower Elbe River in the 10th century A.D. Quaternary International 324, 20–33.

Chapter IV. The palaeoecological development and functioning of the Late Medieval moat – Multiproxy research at Rozprza, Central Poland

Kittel P., Sikora J., **Antczak, O.**, Brooks S.J., Elias S.A., Krąpiec M., Luoto T.P., Okupny D., Pawłowski D., Płóciennik M., Rzodkiewicz M., Stachowicz-Rybka R., Wacnik A. 2018. The palaeoecological development of the Late Medieval moat – Multiproxy research at Rozprza, Central Poland. *Quaternary International* 482, 131-156.

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The palaeoecological development of the Late Medieval moat - Multiproxy research at Rozprza, Central Poland

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ABSTRACT

The Rozprza stronghold functioned as a seat of a noble family since at least the early14th century AD in the form of the motte-and-bailey residence. The remains of the residence are situated in the central part of mid-Luciąża River valley, on the river terrace remnant adjoining a strongly expanding floodplain. The situation and state of preservation give a unique opportunity to conduct research that explain the construction process, detailed history of the medieval moat and palaeoenvironmental reconstruction of the valley floor. Radiocarbon and dendrochronological dating and analysis of artefacts confirmed 14th century age of the moat. Organic deposits (gyttja, peat and organic mud) of moat fill allowed for a set of multiproxy analyses based on sediment cores. The research results indicate shallow water with brief episodes of in-wash in the first stage (13th-14th c. AD), followed by a transformation into telmatic habitat in the second phase of the moat development from 16th-17th c. AD. The deposition of overbank alluvium took place within the moat ditch system as late as the 18th and/or 19th c. AD. We studied the development of this moat environment in the context of valley floor changes.

1. Introduction

Palaeoenvironmental studies of moats are not often undertaken as part of archaeological research of military defensive structures in Central European countries (eg. Beneš et al., 2002; Brown and Pluskowski, 2011; Koszałka, 2014). However, the depositional environment of water-filled moats is very similar to that of small lake basins such as ox-bows, and can be examined with the use of multiproxy palaeoecological methods. Our research at the Rozprza stronghold remnants is one of the first detailed studies on the development of a wet moat environment in the context of natural changes and human impacts in the Late Middle Ages and Modern Times.

Investigations of plant macrofossils were focused on determining the character of local vegetation and its changes during the accumulation of sediments infilling the moat. This small reservoir provides a record of local vegetation changes, which reflects moat functioning from construction to complete infilling by sediment. Pollen analysis, conducted on deposits filling up the moat, allows for the reconstruction of local vegetation evolution and changes in human activity. Cladocera, beetles, Chironomidae and other insects are good palaeoindicators of

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past anthropogenic habitats (Ruiz et al., 2006; Elias, 2015; et al.), shedding a somewhat different light on paleoenvironments. In the case of a moat habitat reconstruction, flooding phases and human influence on aquatic ecosystems, Chironomidae and Cladocera are a key indicators of water level changes (Nevalainen et al., 2011), water inflow (eg. Kittel et al., 2016), water trophic status (eg. Brooks et al., 2001; Luoto, 2011; Kittel et al., 2014) and microhabitat diversity (Armitage et al., 1995). Other aquatic stenotopic insects like beetles and caddisflies, which are less frequently represented in the sediment, give more precise information about presence of certain habitats and adjacent terrestrial environments.

The palaeoenvironmental record of moat fill is very important from the point of view of function and natural evolution of the studied ditch basin, the evolution of the surrounding environment, as well as changes in the Luciąża River valley. This palaeoecological research aimed to support the larger archaeological project investigating the Rozprza stronghold. Our multi-proxy studies were proposed to analyse ecological functioning of the immediate vicinity of the motte, specifically the Luciąża river valley, and the anthropogenic aspects of the landscape evolution. We were particularly interested in the interaction of the economic activity of the Late Medieval communities with the natural environment. We tested whether local river activity (floods, hyporheic flow) was the main factor influencing the moat ecosystem, or whether some human intervention kept the moat in stable condition. We hypothesised that ecological conditions in the moat were poor, driven by strong human impacts. This is why its ecosystem possibly needed to be refreshed by local floods, the inflow of hyporheic waters, or by human activity. We used the moat sediment as an archive of settlers' activity, local agriculture, livestock pasturage, and textile production. All of these activities left evidence in the moat sediment archive.

2. Study area and the study site

The study site (51°18′07″ N; 19°40′04″ E; 182–183 m a.s.l.) is situated in Central Poland, about 60 km south of Łódź. The remnants of a stronghold in Rozprza are located in the middle reach of the Luciąża River (a 3rd-order river in the Vistula River basin) valley floor. The morphology of the valley, and especially of the valley floor, is crucial for the environmental setting of the settlement's location and moat functioning. The region is part of the Odranian (Saalian) formerly glaciated area and the last ice sheet was present there during the Wartanian Cold Stage of the Odranian Glaciation (Marks, 2011). The area is a part of the “European sand belt” (Zeeberg, 1998) characterized by wide-spread fluvial terraces and also aeolian landforms. Intense transformation of river valleys took place under periglacial conditions during the Weichselian glacial period. Two or three terraces existed in most river valleys of the Łódź region (Turkowska, 1988). Three river terraces were recognised by Wachecka-Kotkowska (2004) in the Luciąża River valley in the Rozprza surroundings: the highest is associated with the Wartanian glacifluvial, followed by the higher and lower Weichselian fluvial terraces. The western morainic upland is formed by tills, while the eastern one by glacifluvial sands and gravels (Wachecka-Kotkowska, 2004).

The stronghold's remnants are situated in the central part of the Luciąża River valley (Fig. 1), on the Plenivistulian residual terrace which adjoins a floodplain that likely formed in the Late Vistulian and the Holocene. The valley floor is strongly expanded in the stronghold area (Kittel et al., 2015). According to Wachecka-Kotkowska (2004), the morphology of the valley floor was obliterated by the deposition of modern overbank alluvium. However, this landscape reconstruction has not been confirmed by detailed examination of the surficial geology (Kittel et al., 2015, 2018).

Contemporary climatic conditions in the area are highly variable because of the influence of oceanic and continental air masses. The average annual temperature ranges from 8.6 to 8.9 °C for the neighbouring areas and average annual precipitation varies from 537 to 626 mm per year (http://www.tutiempo.net; date of last access: 11th Dec. 2017). The mean temperature of the warmest month (July) is 18 °C and mean temperature of the coldest month (January) is −3.3 °C for the Lodz region (Kłysik, 2001). Average annual precipitation from 1951 to 1989 was 601 mm for the surroundings of Rozprza (Kłysik, 1993).

The potential natural vegetation of the Luciąża River valley within 5 km of the studied site at Rozprza would be mostly lime-oak-hornbeam forests representing the Tilio-Carpinetum association and to lesser extent the Potentillo albae-Quercetum typicum. In smaller areas, located east and south of Rozprza, Vaccinio uliginosi-Pinetum, Leucobryo-Pinetum and Querco-Pinetum would occur. Terraines near the water courses would be overgrown by lowland ash-alder forests and alder of Fraxino-Alnetum and Carici elongatae-Alnetum associations (Matuszkiewicz, 2008).

According to written sources from the 11th to the 13th c. AD, Rozprza was one of the most important medieval strongholds in Central Poland, next to Łęczyca, Sieradz and Spycimierz (Kamińska, 1953; Kajzer, 2007; Sikora, 2007). It is mentioned for the first time in the “Mogilno Falsification” (1065 AD), then in the “Gniezno Bull” (1136 AD), as a one of the most important princely castles paying tribute to the Mogilno Monastery and the Archbishopric of Gniezno. In the 13th c. it was a seat of castellanus a ducal official, but in the next century it is mentioned as private property of the Nagodzice-Jelitczycy noble family (Zajączkowski, 1961).

The stronghold was first described by Kamińska (1953) as a motte type of earth-work. After the first archaeological excavation undertaken by Chmielowska (1982), this motte phase was dated to the 13th - 14th c. AD. A noble family private residence was built on the site of an older early medieval ring-fort. New research proved that the stronghold functioned as a seat of a noble family in the 14th and 15th c. in the form of motte-and-bailey timber castle (Kittel et al., 2018).

The motte was a pan-European type of fortified residence with artificial mound, in either conical, circular, oval or rectangular shape, usually surrounded by an outer moat and protected by more-or-less complicated systems of additional fortifications, and sometimes with one or more baileys the fortified courtyards. A timber or in later period masonry tower was situated on the mound top, and either formed part of the residential manor building or just a part of a defensive system. Motte features appeared at the turn of 10th and 11th centuries in Northern France and western Germany, in the 11th c. in Flanders and the Netherlands as well as in England (eg. Müller-Wille, 1966; Kenyon, 1990; Higham and Barker, 2004; Aarts, 2007). In Western Europe, motte castles were gradually turned into masonry features or abandoned in 13th −14th c. In the same period they become a popular type of defensive residence in Southern Scandinavia, eastern German countries, the Czech lands (Durdík, 1996), Hungary (Dénes, 2004) and in Poland (Kamińska, 1968; Kajzer, 1993; et al.). Structures analogous to motte type castles even occurred in Western Ukraine (Volyn) (Panyshko, 2014). In 13th c. mottes replaced older timber-earth ringwork castles as ducal residences of minor importance (Kajzer, 1993). Between the 13th and 15th c., timber castles of motte type became the dominant model of knightly residence, especially in the Polish Lowlands.

3. Materials and methods

3.1. Field work and sampling strategy

In recent years, non-destructive research on the stronghold's remnants in Rozprza included detailed geological mapping, large scale aerial photography, and geochemical and geophysical testing. These studies, combined with detailed topographical mapping, uncovered traces of the moat system (Kittel et al., 2015; Sikora et al., 2015). Relicts of the moat system are still clearly visible in the terrain relief, which is currently covered by meadows and fallow fields. A geological survey was carried out in the stronghold's surroundings, in order to

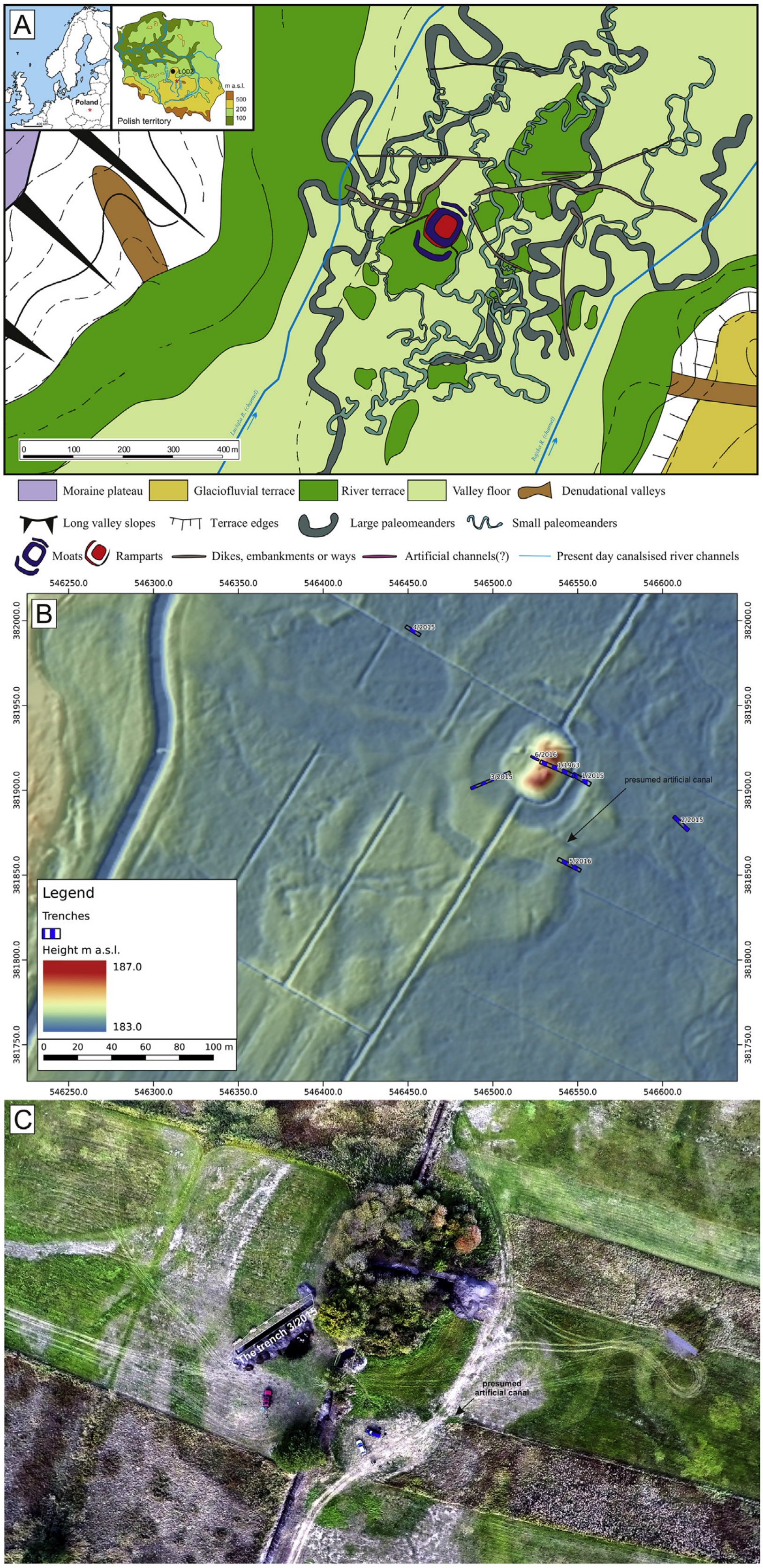
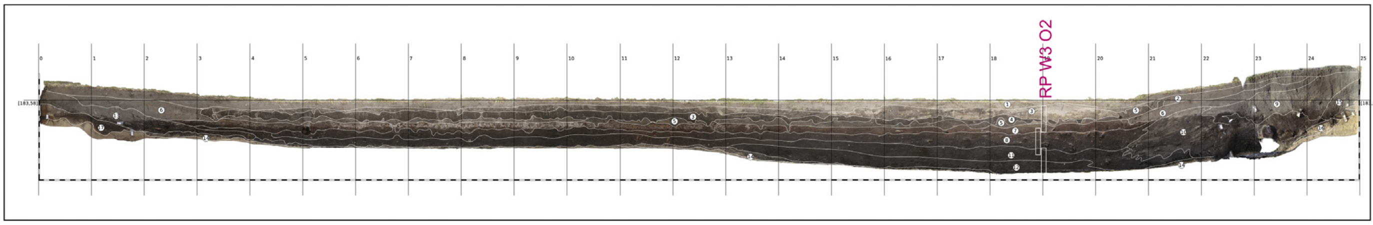


Fig. 1. The characteristic of the site.

A. The geomorphological map of the site vicinity.

B. Digital Elevation Model from Airborne Laser Scanning in the framework of the ISOK program with trenches highlighted with trenches highlighted.

C. An aerial photo taken during excavations in 2015. The Trench 3/2015 with the cross-section of the moat visible (Photo by Wroniecki, 2015).



1 – humic silty sands of plough horizon; 2 – humic sands of earthwork; 3 – silty sands and silts of earthwork from 1944 AD; 4 – overbank sandy organic mud; 5 – overbank sand with organic mud; 6 – humic sands of earthwork; 7 – overbank organic mud with sandy admixtures; 8 – peat; 9 – humic sands with clay admixtures from destruction of the motte rampart; 10 – humic sands of earthwork; 11 – sands laminated with organic mud, with plant detritus; 12 – clayey coarse detritus gyttja with sandy admixtures; 13 – organic mud laminated with sand, with plant detritus; 14 – sand with plant detritus; 15 – humic sands with clay admixtures of the motte rampart; 16 – sand laminated with humic sand; 17 – weakly humic sands with iron precipitation of pit fill

Fig. 2. The cross-section of the main moat of the motte in the Trench 3/2015 (Photo and editing by Sikora 2015).

document the surficial geology in the close proximity to the stronghold (Kittel et al., 2015, 2018). The geological survey with hand augering confirmed the existence of moats filled with organic (gyttja and peat) and partially inorganic deposits rich in remains of woods.

The field work on the moat relict was undertaken in 2015 as an integral part of archaeological investigations of the Rozprza site with the use of trenching (Kittel et al., 2018). Successive 10-cm layers of deposits were removed from the archaeological trench exposure situated across the main motte's moat. Within each 10-cm "mechanical layer", stratigraphic units were distinguished. All excavated deposits were sifted and floated stratum by stratum with the use of a 4 × 4 mm sieve. Waterlogged layers were accessed by pumping water from the excavation. The trenching allowed the recognition of archaeological structures and cultural layers of moat fills in detail. Three excavated archaeological trenches uncovered full cross-sections of the main moat (Fig. 1). The full cross-section through the very well preserved moat at its widest area was reached in trench no. 3/2015 (1.5 × 25 m) situated SW of the stronghold (Fig. 2, Photo 1). Trench 3/2015 allowed detailed examination of the moat-fill. The main moat had a width of almost 21 m and a trapezoidal cross-section with the depth of 0.5 m (the greatest thickness of organic mud, peat and gyttja), up to more than 1.3 m in the centre.

The upper silty-sandy layers mainly contained early medieval potsherds from 11^{th}-13th c., as well as late medieval (14^{th}-15th c.) and modern artefacts. This unit covers a moat fill of organic deposits: peat, gyttja and organic mud with 14th c. artefacts. The modern artefacts provide evidence of the destruction of the western part of the stronghold mound in 1944 AD, so the silty-sandy layers with early medieval materials should be interpreted as redeposited. On the inner moat's slope there was a wooden construction dated to 14th c., which was partly covered with thick layers of slope deposits (various-grained sands laminated with organic mud) from the stronghold earthwork. In the close vicinity of this construction, a large number of pieces of branches and even large fragments of trees were excavated from the layers of organic mud and gyttja. Numerous secondarily discarded pieces of wood and other organic materials were recorded from the moat bottom. They were covered with organic mud and gyttja with a small number of artefacts.

Photo 1. View of the main moat cross-section of the motte in Rozprza (Photo by Kittel 2015).

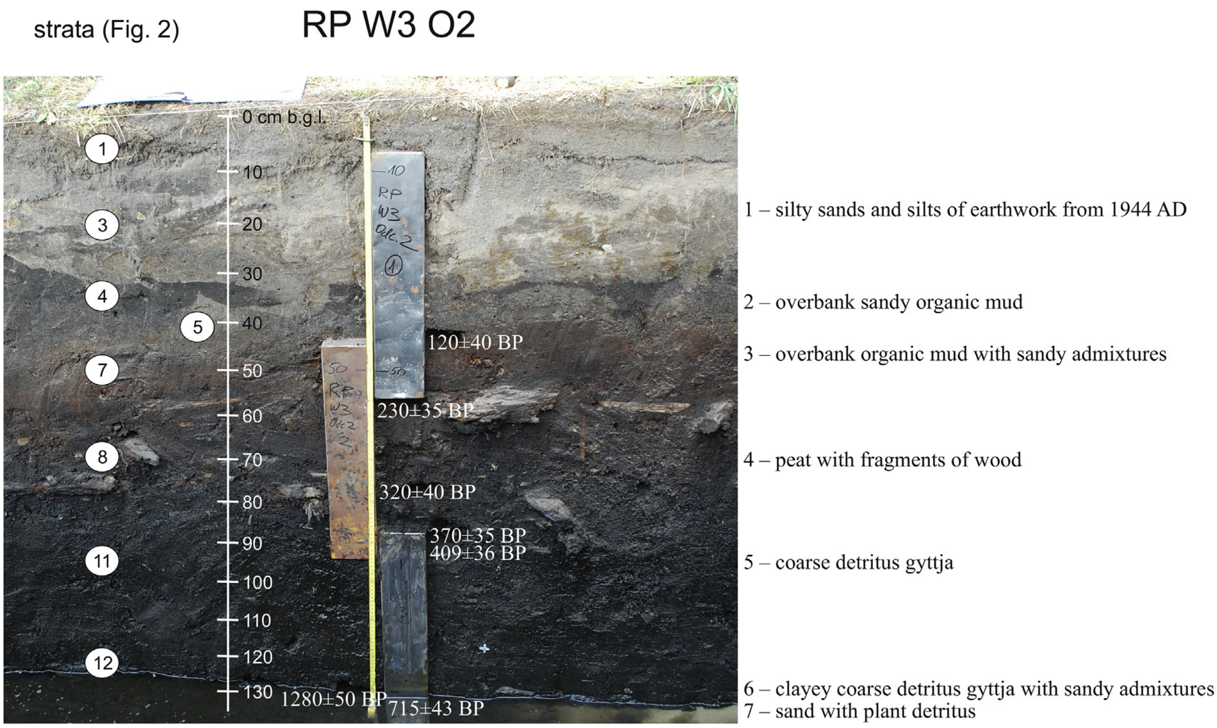


Photo 2. The metal boxes with the core RP W3 O2 of organic deposits collected from the NW wall of the Trench 3/2015 in the deepest part of the main moat fill (Photo by Kittel 2015).

After a full excavation of the moat fills, a core (RP W3 O2) of organic deposits was collected for detailed multiproxy palaeoecological analyses from the deepest part of the moat in trench 3/2015 (Fig. 2, Photo 2). The core was collected as monoliths into three metal boxes with dimensions of 50 × 10 × 10 cm. This method preserves the undisturbed structure of the sediments. The cores cover deposits of the moat fill between 32 and 136 cm below ground level (b.g.l.). A wide range of multiproxy analyses were used to develop a detailed understanding of the history of the moat, based on the core of organic deposits. Successive samples of deposits were taken in 1 cm slices at 2 cm intervals for pollen, diatom, Cladocera analyses and as contiguous 2 cm slice for plant macrofossils, fossil wood and charcoal, subfossil Chironomidae and geochemical analyses. According to the stratigraphic depths associated with the sediments in the core, samples were collected for radiocarbon and dendrochronological datings.

3.2. Palaeoecological analyses

Samples for palynological studies from the RP W3 O2 core contained 1 cm^3 of sediment each and were taken at intervals of 4 cm. Chemical preparation of samples followed the modified Erdtman's acetolysis method (Berglund and Ralska-Jasiewiczowa, 1986), including pretreatment with 40% HF. In order to estimate pollen and non-pollen palynomorph (NPPs) concentrations *Lycopodium* tablets with a specified number of spores were added (Stockmarr, 1971). A minimum of 500 arboreal pollen grains (AP) and all accompanying pollen of terrestrial herbaceous plants (NAP), reedswamp and aquatic plants, as well as spores of cryptogams were counted per sample. Taxonomic identifications were carried out using keys, atlases (eg. Beug, 2004; Reille, 1998), as well as the reference collection of pollen slides.

The basic sum used for percentage calculation consists of pollen grains of terrestrial plants (AP + NAP = 100%). The pollen values of aquatic and wetland plants and spores of cryptogams were determined on the basis of the total sum plus the number of the respective sporomorphs. Local Pollen Assemblages Zones (L PAZ) were distinguished based on both the traditional method of spectra comparison and the ConSLink numerical method.

Samples for plant macrofossil analysis were boiled with KOH to reduce the amount of sediment and remove humic matter, and the material was examined with a microscope. The samples were subject to wet sieve analysis at mesh size of ø = 0.2 mm. Macrofossils were identified using plant keys, atlases (eg. Cappers et al., 2006; Velichkevich and Zastawniak, 2006; Schweingruber et al., 2011), scientific descriptions and publications, as well as a reference collections.

Diatom analysis was conducted according to the method of Battarbee (1986). Samples of 1 cm^3 each from the core were processed. Sediments were treated in 10% HCl to remove calcium carbonate and washed several times in distilled water. Afterwards, the samples were boiled in 30% H_2O_2 in order to digest the organic matter. Finally, the samples were washed several times in distilled water. Permanent microscope slides were mounted in Naphrax. In each sample, approximately 400 diatom frustules were counted in order to estimate the relative abundance of individual taxa. Diatom diversity was measured using the Shannon-Weaver index (H'), which was calculated from relative abundance and species richness values using PAST software (Hammer et al., 2001). Ecological groups of diatoms were determined using OMNIDIA software (Version 4.2) (Lecointe et al., 1993), and then the resulting groups were distinguished according to Denys (1991/2), Dam van et al. (1994), Lange-Bertalot and Metzeltin (1996), Krammer and Lange-Bertalot (2008a, 2008b, 2010, 2011), and Hofmann et al. (2011). Reconstruction of pH was performed using Ernie software (version 1.0) and a combined pH dataset from different regions of Europe (Juggins, 2001). A total of samples made up the combined pH data set. Reconstruction of pH was performed using weighted averaging (WA) regression and correlation. The pH calibration model had a root mean square error of prediction (RMSEP) of 0.5 pH units and a coefficient of determination (r2) of 0.76.

For Cladocera analysis, 1 cm^3 of fresh sediment samples was processed according to standard procedures (Frey, 1986). Initially, samples were treated with hot 10% KOH. The material was then deflocculated using a magnetic stirrer and sieved through a 50 mm mesh. The slides were prepared from 0.1 ml of each sample and examined with a

Table 1
The results of radiocarbon dating of the main moat fill of the Rozprza motte in the Trench 3/2015.

Dated deposits	Profile	Depth b.g.l. [cm]	14C Age yr BP	Laboratory code	Calibrated Age (cal AD, prob. 68.2%)	Calibrated Age (cal AD, prob. 95.4%)	Remarks
top of overbank organic mud	RP W3 O4	38–43	100 ± 40	MKL-2958	AD 1694–1918	AD 1680–1939	
top of overbank organic mud	RP W3 O2	42–47	120 ± 40	MKL-2839	AD 1684–1928	AD 1675–1942	
top of peat	RP W3 O4	50–55	200 ± 40	MKL-2957	AD 1655–1950	AD 1642–1950	
top of peat	RP W3 O2	55–60	230 ± 35	MKL-2840	AD 1643–1950	AD 1526–1950	
bottom of peat	RP W3 O2	75–80	320 ± 40	MKL-2841	AD 1514–1641	AD 1468–1649	
top of coarse detritus gyttja	RP W3 O2	85–90	370 ± 35	MKL-2842	AD 1453–1620	AD 1446–1635	
upper part of coarse detritus gyttja	RP W3 O2	92–94	409 ± 36	MKL-3504A	AD 1439–1614	AD 1429–1630	AMS data of selected plant macro remains (*Rubus idaeus* - 2 seeds, *Solanum nigrum* - 1 seed)
top of coarse detritus gyttja	RP W3 O4	60–65	460 ± 40	MKL-2956	AD 1417–1455	AD 1401–1616	
sand with plant detritus	RP W3 O2	134–136	715 ± 43	D-AMS 016324	AD 1259–1380	AD 1221–1389	AMS data of selected plant macro remains (Rumex sp. - 2 inflorescences, *Chenopodium rubrum* - 1 leaf, *Urtica dioica* - 2 leafs' frgm.)
bottom of clayey coarse detritus gyttja	RP W3 O4	75–80	1190 ± 60	MKL-2955	AD 726–941	AD 687–974	redeposited organic matter
bottom of clayey coarse detritus gyttja	RP W3 O2	130–135	1280 ± 50	MKL-2843	AD 671–770	AD 655–875	redeposited organic matter

microscope (100× magnification). The taxonomy of cladoceran remains in this paper follows that presented by Szeroczyńska and Sarmaja-Korjonen (2007). The ecological preferences of cladoceran taxa were determined on the basis of the published key after Bjerring et al. (2009).

Samples volume for chironomid analysis ranged between 5 cm^3 and 70 cm^3. Preparation methods followed Brooks et al. (2007). After kerosene flotation following the methods of Rolland and Larocque (2007), the sediments were passed through a 56 μm mesh sieve. Identification mainly followed keys by Brooks et al. (2007) and Andersen et al. (2013). Ecological preferences of identified taxa are based mainly on Brooks et al. (2007), Vallenduuk and Moller Pillot (2007), Moller Pillot (2009, 2013). Optimal sum-of-squares partitioning was used to determine zones in the chironomid stratigraphy according to Bennett (1996). The zones were tested for statistical significance with reference to the broken-stick model using ZONE (Lotter and Juggins, 1991) and BSTICK (Line and Birks, 1996) software. Rarefaction of the communities was calculated (n = 72), using PRIMER 6 software (Clarke and Gorley, 2006).

Total phosphorus (TP) (μg/l) was reconstructed using Finnish (Luoto, 2011) and British (Brooks et al., 2001) models. Due to the low Chironomidae concentration in the upper layers of sediments (51-28 cm), reconstructions are limited to depth range 136–55 cm.

Beetles and caddisflies were extracted from the samples taken for chironomid analysis. Specimens were stored in vials of 60% ethanol, and identified on the basis of comparison with modern museum specimens (Elias, 2010).

The pollen, plant macrofossils, diatom, Cladocera and Chironomidae diagrams were plotted stratigraphically in a percentage diagram using POLPAL (Nalepka and Walanus, 2003), TILIA (Grimm, 1992), or C2 (Juggins, 2007) software.

3.3. Numerical analysis

Principal Component Analysis (PCA) and Detrended Correspondence Analysis (DCA) were implemented with CANOCO 4.5 (ter Braak and Šmilauer, 2002) for identification of sources from which the geochemical components were supplied to the studied sediments and to estimate major changes of the proxy assemblages. Standardized values of the contents of LOI, SiO_{2ter}, SiO_{2biog}, pH and 9 macro- and microelements were used as input variables. DCA was used to explore patterns in assemblages and was run with detrending by segments, nonlinear rescaling, and down-weighting of rare species. Pollen percentage values and plant macrofossil count values were square-root transformed. Chironomidae and Cladocera percentage data were not transformed as data range within two orders of magnitude (up to 100%).

3.4. Geochemical and sedimentological analyses

Chemical composition was determined in 58 samples taken every 2 cm after drying at 105 °C and homogenization in agate mortar. Geochemical analysis included identification of: organic matter (loss on ignition method (LOI) in a muffle furnace at a temperature of 550 °C), calcium carbonate – $CaCO_3$ (volumetric method by means of the Scheibler's apparatus), reaction – pH (potentiometric method – in distilled water), biogenic and terrigenous silica – SiO_{2biog} and SiO_{2ter} (methods after: Bengtsson and Enell, 1986). The ash samples were dissolved (with using HCl, HNO_3 and H_2O_2) in Teflon bombs using a microwave mineraliser for 30 samples. The solution obtained was analysed for concentrations of Na, K, Ca, Mg, Fe, Mn, Cu, Zn and Pb, using atomic absorption spectrometry. The proportions of these compounds were used to classify deposits and to reconstruct environmental change in the sedimentologic basin and in the catchment (Pawłowski et al., 2016).

The grain size composition of the ash samples remaining after Loss-on-Ignition analysis was determined using the laser particle size analyzer Mastersizer 3000 with a Hydro MU dispersion unit (Malvern). The textural features, using Folk and Ward (1957) coefficients, were evaluated for 12 samples, for which organic matter content was less than 30%. The relationship between the mean grain size and the sorting index (the so called the co-ordinate system) follows Mycielska-Dowgiałło and Ludwikowska-Kędzia (2011).

3.5. *Geochronology*

3.5.1. *Radiocarbon dating and age-depth model*

Nine selected samples of bulk of organic deposits collected from two profiles in the wall of trench 3/2015 were dated with the radiocarbon (^{14}C) method, using the liquid scintillation technique (LST) and two samples of selected terrestrial plant macrofossils from the RP W3 O2 core using accelerator mass spectrometry technique (AMS) (Table 1).

Conventional radiocarbon dating of organic material using the liquid scintillation counting method (LSC) was performed in the Laboratory of Absolute Dating, in Krakow (Poland). Samples were chemically pre-treated with the AAA (acid-alkali-acid) method. The procedure included the standard synthesis of benzene from organic samples (Skripkin and Kovalyukh, 1998). ^{14}C measurements were carried out with a 3-photomultiplier spectrometer, the HIDEX 300SL (Krąpiec and Walanus, 2011) and Quantulus 1220. Dating using the AMS technique was made in the Accelerator Mass Spectrometry Laboratory in Seattle (D-AMS signature) (see Zoppi et al., 2007 for details).

Calibrated radiocarbon ages (cal yr BP) were made using the IntCal13 radiocarbon calibration dataset (Reimer et al., 2013) and the OxCal 4.2 calibration software (Bronk Ramsey, 2009). All presented margins of error are the uncertainties at a 68.2% probability.

The chronology (age-depth curve) of the RP W3 O2 core is based on the OxCal P_Sequence model (Bronk Ramsey, 2008). In total six radiocarbon dates were used for the construction of the age-depth model (Table 1). The changes in the pattern of accumulation (eg. from peat to gyttja) were taken into account during the age-depth model construction. Therefore, in our model, single-boundary constraints were introduced, assigned to the depths of 55 cm (Fig. 3). On the basis of the age-depth model, we calculated the probability distributions of the modelled calendar ages for selected events related to the local palaeoenvironmental changes.

3.5.2. *Dendrochronological methods*

Dendrochronological analyses of 20 wood samples from trenches 1/2015 and 3/2015 (Table 2) were performed using standard research procedures (Schweingruber, 1988). Two to four measurement trials were made on each of the samples, along the radii. Then, each of the samples was subjected to a measurement of the annual growth rings to an accuracy of 0.01 mm using the Dendrolab 1.0 apparatus (Zielski and Krąpiec, 2004). For the dendrochronological measurements, and for the processing of the measured tree-ring sequences, the TREE-RINGS computer software suite was used (Krawczyk and Krąpiec, 1995), as well as the TSAP software (Rinn, 2005). Absolute dating of oak samples was made against the Wielkopolska standard (Krąpiec, 1998).

4. Results

4.1. *The age of the moat fill*

The medieval age of the feature (i.e. studied moat) was previously established by radiocarbon dating of samples collected from the bottom of the main moat's fill with the use of hand auger: 1080 ± 60 BP, i.e. 895–1017 AD (prob. 68.2%) and 1040 ± 60 BP; i.e. 897–1038 AD (Kittel et al., 2015, 2018). The ^{14}C dates from the wall of the trench 3/2015 are presented in Table 1. The results of datings from the moat's bottom are 1190 ± 60 BP, i.e. 726–941 AD (prob. 68.2%) and 1715 ± 43 BP, i.e. 671–770 AD (prob. 68.2%). However, most results are from 460 ± 40 BP to 100 ± 40 BP. The ^{14}C data obtained from the selected terrestrial plant macrofossils from the bottom of the RP W4 O2 core is 1280 ± 51 BP, i.e. 1259–1380 AD (prob. 68.2%). Those results document the existence of the moat almost since the 14th c. AD (Fig. 3, Table 1).

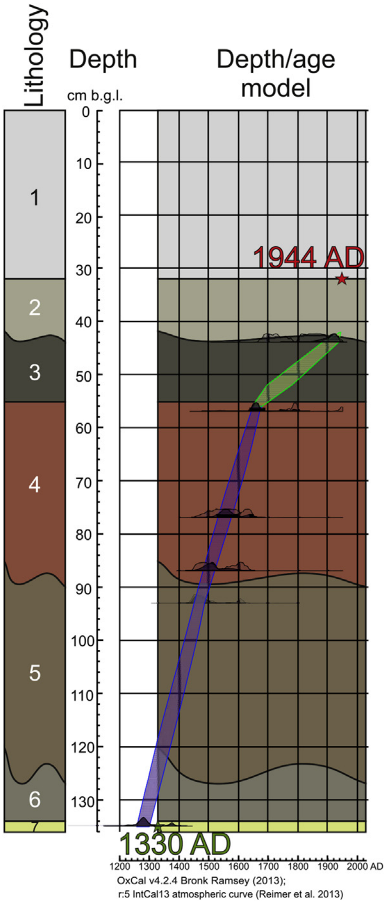


Fig. 3. The depth/age model for the deposits of the main moat fill in core RP W3 O2 (prepared by M. Krąpiec).
Lithology: 1 – silty sands and silts of earthwork from 1944 AD (strata 1 and 3 on Fig. 2); 2 – overbank sandy organic mud (strata 4–5); 3 – overbank organic mud with sandy admixtures, with numerous fragments of wood and roots (strata 7); 4 – peat with fragments of wood (strata 8); 5 – coarse detritus gyttja (strata 11); 6 – clayey coarse detritus gyttja with sandy admixtures (strata 12); 7 – sand with plant detritus (strata 14).

The artefacts discovered within the moat's fill are not older than the 14th c. Therefore, ^{14}C dates obtained from the very bottom of the moat fill are too old, as a result of the re-deposition of organic matter from older humic horizons and a cultural layer in the beginning of the moat's existence. This also explains the spuriously old dates that were obtained previously from organic deposits from the hand-auger cores.

Six oak poles of the construction on the moat slope in the trench 3/2015 were dendrochronologically dated to: 1296, 1274 (−6/+8), 1307 (−4/+8), 1311 (−4/+8), after 1332 and 1333 (−5/+8) AD (Fig. 4, Table 2). In the very bottom of the moat in trench 3/2015, fragments of oak wood dated to 1329 AD has been found. Wooden construction elements in the trench 1/2015 were dated to: 1245, 1309, 1310, 1307 (−4/+8), 1325 (−5/+8), 1322 (−5/+8), 1333 (−5/+8), after 1304, after 1322, after 1336 and also 1581 (−5/+8) AD (Fig. 5, Table 2). The fragments of wooden elements discovered in the very bottom of the moat in trench 1/2015 were dendrochronologically dated to "after 1298 AD". Within organic deposits of the moat fill, numerous wood fragments were dated to the 14th c.

The dendrochronological datings results show that the studied moat

Table 2
The results of dendrochronological dating of wood elements from the main moat of the Rozprza motte in the Trench 3/2015 and the Trench 1/2015 (analysis by M. Krąpiec & E. Szychowska-Krąpiec).

Location of the sample	Wood fragment no. or location in the trench	Laboratory code	Type of wood	Number of tree-rings	Sapwood	Dating of the tree-rings sequences [AD]	Dating of felling tree [AD]
trench 3	228	ROZP86	Quercus sp.	79	–	1171–1249	after 1256
trench 1	298	ROZP52	Quercus sp.	133p	126–133	1177–1309	1309
trench 3	318	ROZP53	Quercus sp.	119	111–119	1185–1303	1307 (−4/+8)
trench 1	297	ROZP56	Quercus sp.	59p	52–59	1187–1245	1245
trench 3	coarse detritus gyttja (80–90 cm b g.l.)	ROZP79	Quercus sp.	109	–	1191–1299	after 1309
trench 1	291	ROZP48	Quercus sp.	128	121–128	1192–1317	1322 (−5/+8)
trench 3	238	ROZP39	Quercus sp.	74	68–74	1195–1268	1274 (−6/+8)
trench 3		ROZP72	Quercus sp.	93	–	1200–1300	after 1307
trench 1	289	ROZP50	Quercus sp.	128	121–128	1201–1328	1333 (−5/+8)
trench 3	328	ROZP47	Quercus sp.	99	91–99	1209–1307	1311 (−4/+8)
trench 3	236	ROZP46	Quercus sp.	116	109–116	1213–1328	1333 (−5/+8)
trench 1	250	ROZP60	Quercus sp.	84	–	1214–1297	after 1304
trench 3	244	ROZP87	Quercus sp.	79	62–79p	1218–1296	1296
trench 1	281	ROZP42	Quercus sp.	90	79–90p	1221–1310	1310
trench 1	293	ROZP76	Quercus sp.	76	–	1246–1329	after 1336
trench 3	319	ROZP88	Quercus sp.	64	–	1252–1315	after 1322
trench 1	287	ROZP51	Quercus sp.	68	61–68	1253–1320	1325 (−5/+8)
trench 3	overbank deposits	ROZP82	Quercus sp.	74	–	1254–1327	after 1335
trench 3	sand with plant detritus in the bottom of the moat (120–130 cm b g.l.)	ROZP62	Quercus sp.	72	63–72p	1258–1329	1329
trench 1	283	ROZP40	Quercus sp.	108	101–108	1469–1576	1581 (−5/+8)

p – the youngest underbark tree-ring.

in Rozprza was established most probably ca. 1330 AD and older wooden elements from the 2nd half of 13th and the beginning of 14th c. were used for constructions too.

The fill of the main moat in the RP W3 O2 core consists of (Fig. 3, Photo 2):

1 – silty sands and silts of earthwork from 1944 AD (at a depth 0–32 cm b g.l.) – strata 1 and 3 on Fig. 2;
2 – overbank sandy organic mud (32–42/44 cm b g.l.) – strata 4 and 5;
3 – overbank organic mud with sandy admixtures, with numerous fragments of wood and roots (42/44–55 cm b g.l.) – strata 7;
4 – peat with fragments of wood (55–85/90 cm b g.l.) – strata 8;
5 – coarse detritus gyttja (85/90–120/127 cm b g.l.) – strata 11;
6 – clayey coarse detritus gyttja with sandy admixtures (120/127–134 cm b g.l.) – strata 12;
7 – sand with plant detritus (134–136 cm b g.l.) – strata 14.

All of these deposits were accumulated in the last ca. 700 years, as documented by radiocarbon (^{14}C) and dendrochronological data (Tables 1 and 2), as well as artefacts. The beginning of moat exiting is

Fig. 4. The NE sector of Trench 3/2015 with timber construction and dendrochronological and radiocarbon data (Photo and editing by Sikora 2015).

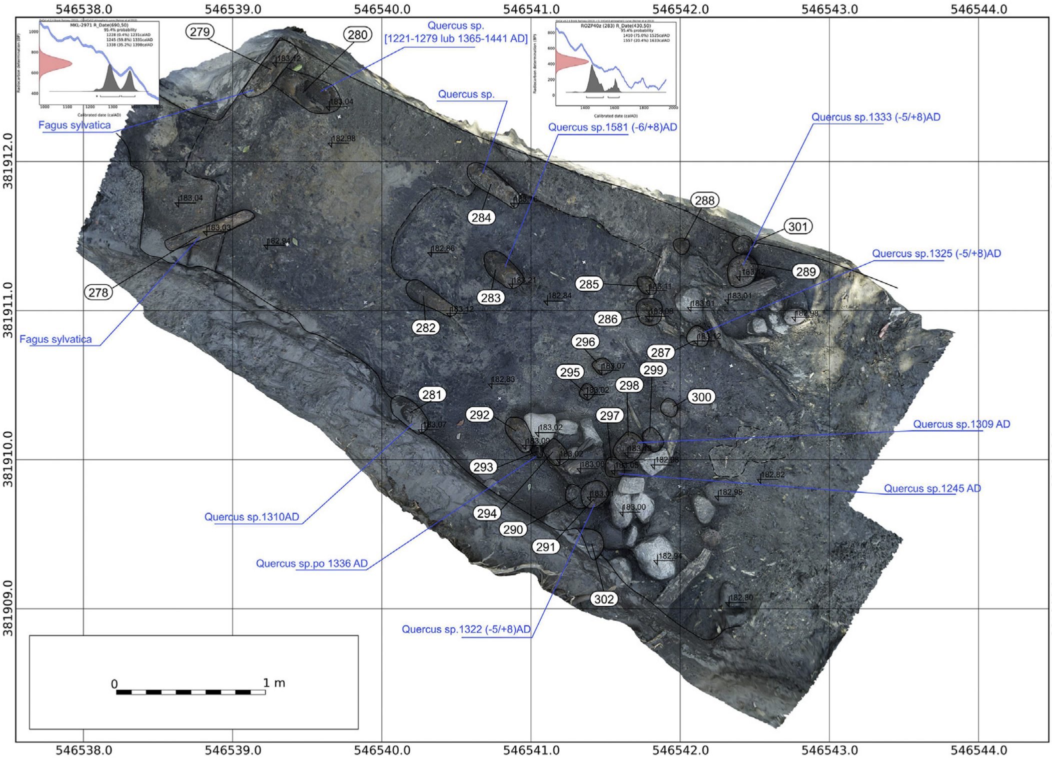


Fig. 5. The W sector of Trench 1/2015 with timber construction and dendrochronological data (Photo and editing by Sikora 2015).

defined to ca. 1330 AD. The age-depth curve demonstrates that the change of deposition from the coarse-detritus gyttja to the peat (ca. 85/90 cm b g.l.) took place ca. 1500 AD and the accumulation of overbank deposits started after ca. 1700 AD.

4.2. Geochemistry of the moat fill and palaeoecological results

Based on variations in the chemical composition of deposits and the macro- and microelements contents in the RP W3 O2 core, four main **geochemical** zones are distinguished (Table 3, Fig. 6).

The pollen analysis showed the presence of 124 vascular plants taxa, cryptogams and fungi in the sediments filling up the moat. The pollen sequence represents five distinct periods of vegetation changes in the direct vicinity of the Rozprza stronghold (Table 3, Fig. 7).

Analysis of **plant macrofossils** in the sediments infilling the moat revealed a succession of local vegetation, recorded in seven vegetation zones marked as L MAZ R 1–7 (Table 3, Fig. 8) The division was based on the occurrence of the one or more of the most abundant,

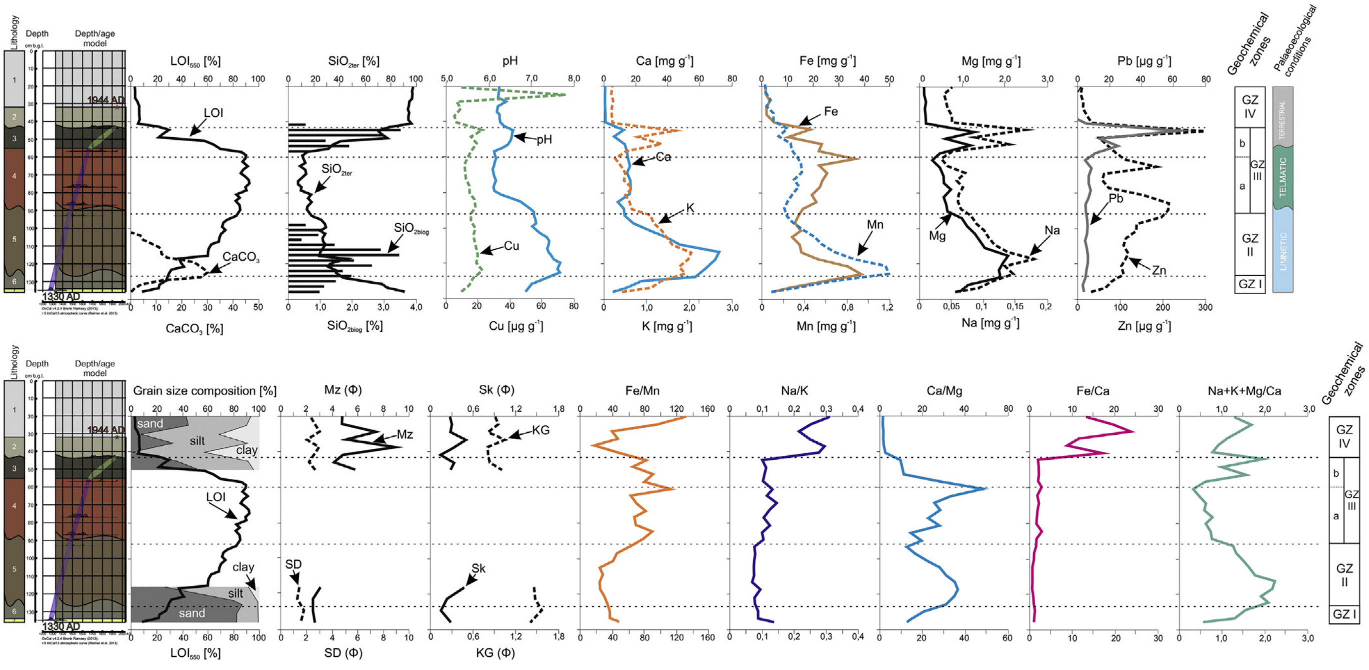


Fig. 6. Results of geochemical analysis of deposits from the RP W3 O2 core (analysis by D. Okupny).

Table 3
The results of palaeoecological (plant macrofossils, diatoms, cladocerans, chironomids, beetles and caddisflies, pollen) and geochemical data form core RP W3 O2 at Rozprza site.

Depth/Age	Geochemistry	Plant macroremains	Diatoms	Cladocera	Chironomidae	Pollen
136–130(125) cm = 1st half of 14th c. AD	GZ 1 (136-127 cm):	L MAZ R 1 (136-132 cm)	D 1a (135-130 cm)	Cl 1 (135-125 cm)	Ch1 (136-85 cm)	L PAZ R 1, *Pinus-Alnus-Quercus* (*Betula*), (135-99 cm)
	- Gradual increase of most elements, mainly LOI (from 8.71 to 27.8%) and $CaCO_3$ (from 1.41 to 12%).	- Only single taxa in the distinguished ecological groups.	- The frequency fluctuated from $0.8 \times 10^6\,cm^{-3}$ to $17.3 \times 10^6\,cm^{-3}$.	- littoral, mainly macrophyte/sediment-associated taxa dominated, with *Alona rectangula*, and *Chydorus sphaericus*, as well as macrophyte-associated taxa as *Acroperus harpae*, and *Alonella nana*. Sediment-associated taxa such as *Pleuroxus trigonellus* and *Leydigia acanthocercoides* were also noted.	- The highest species richness. Rarefaction reach 33.1 (mean 27.2).	- The high concentration of pine (*Pinus sylvestris*) and alder (*Alnus*) pollen grains with the growing tendency of *Alnus*.
	- Low concentrations of SiO_{2biog} and Pb.	- Presence of fruitlets of *Alnus glutinosa*.	- Number of taxa varied between 35 and 44.	- Pelagic forms are absent besides sporadic occurrence of *Simocephalus* sp.	- Phytophilous species typical to permanent stagnant water dominated, e.g. *Paratanytarsus penicillatus*-type, *Glyptotendipes pallens*-type and *Cricotupus intersectus*-type.	- Strong increase of willows (*Salix*) pollen amount in the upper part of the zone.
	- The mean Fe/Mn, Na/K and Fe/Ca index reaches the lowest values in the whole core. Inorganic admixtures of these deposits represent vari-grained sands. The median (Mz): 2.54–3.18 phi.	- Plants preferring high-trophy habitats: *Chenopodium* t. *album*, *Ch.* t. *rubrum*.	- pH: alkaliphilous diatoms dominated (e.g. Cocconeis placentula var. lineata, Gomphonema acuminatum, G. angustum), but alkalibiontic (e.g. *Epithemia turgida*) and circumneutral (e.g. *Aulacoseira crenulata*) taxa also occurred.		- High abundance of Tanypodinae suggests ample meiobenthos communities.	- Considerable but decreasing frequency of birch (*Betula*) (from 15% to 3%) and oak (*Quercus*) (from 7% to 3%).
		- In the bulrush zone occurred Phragmites australis, Mentha aquatica and Hydrocharis morsus-ranae. - Aqueous plants: the endocarps of *Potamogeton friesii*, *P. pusillus*, and the oospores of the Characeae.	- Among all taxa with known trophic preferences, eutraphentic taxa were the most abundant (43.4–55.3% average abundance). - DI-pH was 8.0–8.3.		- Presence of taxa inhabiting mineral bottom (e.g. Micropsectra pallidula-type, M. contracta-type, Tanytarsus chinyensis-type and Paratendipes albimanus-type). Trophy reconstructions indicate the state of permanent eutrophy (Finnish model), reaching hypertrophy (British model).	- Continuous curves formed by hazel (*Corylus avellana*), hornbeam (*Carpinus*), spruce (*Picea abies*), and elm (*Ulmus*). - Regular occurrence of arboreal pollen of: beech (*Fagus sylvatica*), lime (*Tilia cordata*), fir (*Abies alba*) and ash (*Fraxinus*).
		L MAZR 2 (132-126 cm)	- The Shannon-Weaver Diversity Index (H′) varied 2.86–3.13, with average value of 2.96		- According to the British reconstruction, the Ch1 phase started with hypertrophy (up to 188.4 μg TP/l), which decreased between 119 and 85 cm (14th/15th century AD), but has an increasing tendency (visible in both reconstructions)	- Constant presence of pollen of cultivated plants, such as: rye (*S. cereal*), wheat (*Triticum* type) and hemp/hop (*Cannabis/Humulus*).
		- Distinct increase in the contribution of: plants from arid habitats, plants related to the humans, and Characeae oospores. - Wood fragments of *Alnus glutinosa* and *Salix* sp.				- Ruderals and weeds: high values of *Artemisia* (up to 8%) and regular presence of *Rumex acetosella* type, *Centaurea cyanus* and Chenopodiaceae. - The share of pollen of grassland taxa fluctuates within a few percent.

(*continued on next page*)

Table 3 (*continued*)

Depth/Age	Geochemistry	Plant macroremains	Diatoms	Cladocera	Chironomidae	Pollen
		- Increased content of *Urtica dioica* and *Chenopodium* t. *album.*				- Aquatic plants are represented by vascular plants (e.g. *Alisma*, *Potamogeton*, *Sparganium* type, *Stratiotes*) and algae (*Pediastrum*, *Gloeotrichia*).
		- Presence of *Hypericum perforatum*, Capsella bursa-pastoris, Fragaria vesca/viridis; single diaspores of peat plants, e.g. Carex acuta and Juncus sp. - Numerous endocarps of *Potamogeton friesii* and Characeae oospores among the aqueous plants. - Numerous ephippia of *Daphnia.*				- Spores of *Glomus* are regularly present.

Depth/Age	Geochemistry	Plant macroremains	Diatoms	Cladocera	Chironomidae	Pollen
129(125) – 81(93) cm = 2nd half of 14th – 1st half of 16th c. AD	GZ 2 (127-92 cm)	L MAZ R 3 (126-108 cm)	D 1b (129-101 cm)	Cl 2 (125-81 cm)	Ch1 (136-85 cm)	L PAZ R 1, *Pinus-Alnus-Quercus* (*Betula*), (135-99 cm)
	The two subzones can be distinguished:	- Increased contribution of aqueous plants (*P. acutiformis*, *P. natans*, *Nr lutea*, *S. erectum,* and *L. trisulca*), abundant oospores of Characeae.	- Increase of some planktonic taxa, e.g. *Ellerbeckia arenaria* and *Aulacoseira granulata.*	- Cladocera numbers increased (over 8500 specimens and 14 species per cm^3).	- see above-	- see above-
	- The bottom part is composed mainly of SiO_{2ter} (37.4–44.6%), being replaced by increasing concentrations of lithophilic elements: Na, K and Mg as well as of SiO_{2biog}, Ca, Fe and Mn.	- Numerous remains of plants from arid habitats.	- Domination of diatoms preferring various water pH level. The relatively stable frequency of alkaliphilous, circumneutral and alkalibiontic species almost up to the upper part of the zone.	- Littoral species are dominated by *Ch. sphaericus*, *Alona affinis*, and *Ac.harpae.*		
	- In the top part (above 112 cm) is dominated by organic matter (LOI 62.8–82.4%), with admixtures of SiO_{2ter} (ca. 20%) and $CaCO_3$ (0–7%).	- In the most abundant group of plants related to human activity occurred e.g. seeds of *C. bursa-pastoris* and *U. dioica.*	- Domination of eutraphentic species (e.g. *A. crenulata, Sellaphora pupula, G. acuminatum*).	- Macrophyte-associated taxa (e.g. *Graptoleberis testudinaria*, *Camptocercus rectirostris*) were also significant.	In both Ch1 and Ch2 zones occur regularly, although in small amounts, some fluvial morphospecies.	L PAZ R 2, *Salix* (99-87 cm)
	- A significant enrichment of LOI accompanied by decreased contents of SiO_{2biog}, Na, K, Mg, Ca, Fe and Mn.	- Increased contribution of trees and shrubs (*Salix* sp., *A. glutinosa*, *Betula* sect. *albae*, *C. sanguinea*, *F. alnus*, *R. caessius* and *R. idaeus*).	- The frequency of diatoms increased from 5.3 × 10^6 cm^{-3} to 242.9 × 10^6 cm^{-3} at the start, and decreased (95.8 × 10^6 cm^{-3}) at the end of subphase.	- Sediment-associated taxa, Disparalona rostrata, Pleuroxus uncinatus and L. acanthocercoides are observed.	- Typically rheobiontic taxa (*Rheotanytarsus*, *Rheocricotopus fuscipes*-type and *Corynoneura lobata*-type) appear only as a single head capsules on different depths.	- The sharp increase and maximum value of *Salix* pollen (up to 33%).

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Table 3 (*continued*)

Depth/Age	Geochemistry	Plant macroremains	Diatoms	Cladocera	Chironomidae	Pollen
		- Peat plants include Carex rostrata, C. pseudocyperus and Caltha palustris.	- Number of taxa varied between 32 and 53.	- Pelagic forms, *Bosmina longirostris*, *Daphnia pulex* and *Simocephalus* sp., occur occasionally.	- Rheophilic taxa, inhabiting mainly (but not only) running water, are represented by *Nanocladius rectinervis*-type, *Diplocladius* and *Eukiefferiella.* Typically rheophilic are also *Corynoneura coronata*-type and many species from *Thienemannimyia* group, which were found from 119 up to 55 cm (2nd half of 14th – 17th c. AD).	- The concentration of *Alnus* rapidly declines from 18% to 13%.
		L MAZ R 4 (108-92 cm)	- Slightly alkaline environment (DI-pH 7.3–8.0).		- More significant is presence of more eurytopic taxa, such as *Psectrotanypus varius.*	- The highest value of *Cannabis/Humulus* pollen (up to 6%) is observed despite the general slight decrease of the herbaceous plants frequency.
		- The highest contribution of trees and shrubs in the entire succession. *Salix* sp. *A. glutinosa*, and *Cornus sanguinea* dominated; *F. alnus*, *S. nigra*, *Rubus fruticosus*, *R. caessius* and *R. idaeus* were also present.	- the Shannon-Weaver Diversity Index (H′) varied 2.87–3.45, with average value of 3.16.		- Paramerina/	- Pollen and other microremains of aquatic and swamp taxa, e.g. *Potamogeton*, *Nuphar*, Nympeaceae, *Stratiotes aloides*, *Lemna*, *Rumex aquaticus type*, *Typha latifolia* are present.
		- The highest contribution of fruitlets of *Cannabis sativa*; sporadic occurrence of *Linum usitatissimum* fruitlets.	D 1c (99- 93 cm)		*Zavrelimyia* and *Micropsectra* are connected with oligotrophic conditions or streams and rivers. Here they should be treated as the indicators of fluvial habitat.	
		- High values of U.dioica, P.major, Ch. glaucum and R.crispus. - In the top part the contribution of *C. rostrata* and aqueous plants significantly increased	- The increase of planktonic species at the top of subphase (34.8% average abundance). - Domination of alkaliphilous and alkalibiontic species.			
		- In the top of the succession the content of the content of *L. trisulca*, *A. plantago-aquatica*, *Potamogeton compresus*, *P. acutiformis* increased, whereas the contribution of Characeae decreased to their complete disappearance.	- Domination of eutraphentic and increase of oligotraphentic and *meso*-eutraphentic species at the top of this zone.			
		- Nuphar lutea, Najas marina and Sparganium erectum occurred.	- The most abundant are: *A. granulata*, A. crenulata, C. placentula var. lineata, E. arenaria, G. truncatum, Staurosira construens. - Lower diatom valve concentration.			

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Table 3 (*continued*)

Depth/Age	Geochemistry	Plant macroremains	Diatoms	Cladocera	Chironomidae	Pollen
			- At the beginning the frequency of diatoms reached $54.1 \times 10^6\,cm^{-3}$, and decreased ($4.4 \times 10^6\,cm^{-3}$) at the end. - The DI-pH decreased from 8.0 to 7.5 - Increase of the Shannon-Weaver Diversity Index (H′), and varied between 2.74 and 3.23, with average value of 2.97. - Number of taxa varied between 34 and 50.			

Depth/Age	Geochemistry	Plant macroremains	Cladocera	Chironomidae	Coleoptera/Trichoptera	Pollen
81(92) – 56(43) cm = 2nd half of 16th – 19th c. AD	GZ 3 (92-43 cm) Geochemical stratification reflects two subphases (GZ 3a and GZ 3b) evolution of the reservoir.	L MAZ R 5 (92-70 cm) - A significant increase of the contribution of plants from peatland habitats, such as *Carex rostrata.*	Cl 3 (81-61 cm) - Cladocera numbers rapidly decreased, not exceeding 1000 specimens and 8 species per cm^3.	Ch 2 (85-53 cm) - Taxa richness decreased (mean rarefaction 15.8), but abundance of Chironomidae still remained high.	B 1 (78-76 cm) - This assemblage includes the water beetles *Coelostoma orbiculare* and *Graphoderus,* living in stagnant water amongst dense vegetation and/or plant debris.	L PAZ R 3, *Corylus-Pinus-Quercus* (87-63 cm) - The sharp increase of the concentration of hazel *Corylus avellana* (up to 35%) and *P. sylvestris* pollen (up to 53%) occurs parallel with the decrease of *Salix*, *Alnus*, and *Betula.*
	- The contents of the organic matter increased (LOI from 82.3 to 92.1%).	- A decrease of abundance and taxonomic variability among plants from arid habitats and related to human activity. Single diaspores of *Capsella bursa-pastoris*, *Urtica dioica*, *Solanum dulcamara*, *Scirpus sylvaticus*, *Ranunculus lingua* and *Pimpinella major.*	- Macrophyte/sediment-associated taxa as *A.affinis*, *A. rectangula* and *Ch. sphaericus* dominated.	- A few semiterrestrial taxa appeared (mostly Parametriocmenus-Paraphaenocladius and Limnophyes-Paralimnophyes).	- The rove beetle *Atheta*, the marsh beetle *Cyphon*, the dung beetle *Aphodius* are associated with terrestrial habitats	- Slight increase of *Quercus* frequency (up to 5%).
	- The concentration of K, Mn, K and Na decreased.	- Decrease of abundance and taxonomic variability among trees and shrubs. The presence of *A. glutinosa*, *Prunus padus* and *Frangula alnus* has been noted.	- Except for *Simocephalus* sp., pelagic forms are nearly absent.	- Less species living on plants, but some taxa (e.g. *Phaenopsectra flavipes*–type, *Corynoneura arctica*-type and *P. penicillatus*-type) occur regularly.	- The material of the caddisfly larvae in the family Limnephilidae was not sufficient to make a specific identification.	- *Fagus* and *Picea* pollen are regularly present as well as *Viburnum* and *Frangula.*
	- Towards the top of zone, increased concentration of lithophilic (Na, K, Mg) and trace elements (Cu, Zn, Pb).	- Single seeds of A. plantago-aquatica, Sparganium erectum, Lemna trisulca, *L. minor* and Ceratophyllum demersum among the aqueous plants.	- At the end of zone, only one littoral taxon, *Ch. sphaericus* is observed.	- Presence of taxa typical to mineral bottom (e.g. *Thienemannimyia* group, *Micropsectra junci*-type).	B 2 (56-54 cm)	- Among NAP is a higher representation of cultivated plants such as *Secale cereale* (up to 3%) and *Triticum* type (up to 2%). Single *Fagopyrum* pollen appears. *Cannabis/Humulus* disappears at the end of the zone.
	- The Fe/Mn and Ca/Mg values were slightly higher than in the underlying coarse-detritus gyttja, and a sharp maximum (112.3 and 48.1 respectively) was located at the top of peat layer (depth: 62-60 cm).	L MAZR 6 (70-56 cm)	Cl 4 (61-47 cm)	In both Ch1 and Ch2 zones occur regularly, although in small amounts, some fluvial morphospecies (see above)	– Presence of the water beetle *Hydraena riparia* and Limnephilidae caddisfly, typical to the shallow waters of ponds and lakes.	- Among the group of ruderals and weeds occur mostly *Artemisia* (up to 3%), *Rumex acetosella* type (up to 2%), *Polygonum aviculare* type and *Centaurea cyanus* pollen.

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Table 3 (*continued*)

Depth/Age	Geochemistry	Plant macroremains	Cladocera	Chironomidae	Coleoptera/Trichoptera	Pollen
	- The Na + K + Mg/Ca ratio (an indicator of erosion rate) was high at 55-43 cm, with a maximum of 1.65 at the end of this period	- A similar contribution among trees and shrubs (*A. glutinosa*, *P. padus*, *F. alnus*, *Cornus sanguinea*, *Sorbus acuparia* and *Rubus idaeus*) as in the previous zone.	- only a few littoral, macrophyte- and macrophyte/sediment-associated taxa are observed.		B 3 (52-50 cm) – Presence of the water the water beetles, *Helophorus* (associated with shallow, mud-bottom ponds) and Hydraena *riparia* (overgrown stream-fed ponds).	- Higher values of grassland taxa, especially Poaceae, Cyperaceae and *Filipendula.*
		- Humid habitats: the increase of Ranunclus acris, R. flammula, R. lingua and Sium latifolium.	- Ch. sphaericus and *A. affinis* are dominated.	Trophy reconstructions indicate the state of permanent eutrophy (Finnish model), reaching hypertrophy (British model).	- The rove beetles: *Lathrobium* are associated with damp habitats, and *Stenus* are all shore-dwellers (both running and standing water).	- *Plantago lanceolata* forms continuous curve with values up to 1.5%.
		- Domination of peat plants, mainly *C. rostrata* and *Menyanthes trifiliata.*	- The frequency of cladoceran do not exceed 800 specimens cm^{-3}.	- In Ch2 phase trophy rapidly grows and at 79 cm (ca. 1550 AD) exceeds 200 µg TP/l. The peaks in Finnish model are at 79 cm	B 4 (48-46 cm)	- The highest frequency of *Equisetum* spores (up to 21%).
		- Few taxa of aqueous plants, mainly *A. plantago-aquatica* and *Potamogeton acutiformis* in the base of the zone.			- This level contains the ground beetle *Trechus rubens* and the rove beetle *Arpedium quadrum.* Both species are widespread in Europe today and they live in damp habitats, often near rivers or streams. *T. rubens* lives in clay-rich soil with damp leaf litter. *A. quadrum* is typically found in birch forest regions.	L PAZ R 4, *Salix-Pinus-Alnus* (*Corylus*) (63-51 cm)
						- Significant re-growth of *Salix*, *Alnus* and *Corylus.* - Concentration of *Pinus sylvestris* reached 50%. - Frequency of *Betula*, *Quercus* and *Picea* decreased slightly. - Representation of terrestrial herbaceous plants, as well as aquatic and swamp taxa decreased.

Depth/Age	Geochemistry	Plant macroremains	Chironomidae	Pollen
56(43) – 32 cm = 19th c. AD – 1st half of 20th c. AD	GZ 4 (43-32 cm) - The highest content of SiO_{2ter} (93.1–96.8%) and low content of biogenic components (SiO_{2biog} and organic matter).	L MAZ R 7 (56-34 cm) - The contribution of plant macroremains (particularly peatland plants), and the taxonomic diversity of the remaining groups distinctly decreased, particularly in the top of the zone.	Ch3 (53-32 cm) - sudden decrease of Chironomidae abundance.	L PAZ R5, *Pinus*-NAP (51-33 cm) - Sporomorphs are partly corroded. In three samples pollen concentration was too low to be counted so the record is discontinuous.
	- The concentrations of K, Ca, Fe, Mn and Mg are low, while the contents of other elements fluctuate around their average values calculated for the whole core.	- Fruitlets of *A. glutinosa* were still present. *Sambucus nigra*, *Rubus cassius* and *R. idaeus* appeared.	- Only singular head capsules of taxa typical for telmatic habitats (*Limnophyes-Paralimnophyes*, *Pseudosmittia* and *Pseudorthocladius*) and a few Chironomini (*Dicrotendipes notatus*-type, *Chironomus* and *Polypedilum nubifer*-type) tolerant to eutrophic conditions, have been recorded.	- The highest in the profile value of *P. sylvestris* (up to 56%) and a sharp increase of NAP values. Especially high concentration in the grassland group: Poaceae, Cyperaceae, Cichorioideae, Rubiaceae, Brassicaceae.

(*continued on next page*)

Table 3 (*continued*)

Depth/Age	Geochemistry	Plant macroremains	Chironomidae	Pollen
	- The content of Cu reaches high values (to 76.6 μg/g), while the concentrations other trace elements are very low (Zn) or completely lacking (Pb). - The sediments represent very weakly sorted sandy silt (Mz: 4.18–9.00 phi; SD 2.04–3.03 phi).	- Herbaceous plants: single occurrences of Lapsana communis, Lamium maculatum, Solanum dulcamara, Rananculus flammula and Sium latifolium. - Peatland plants: the contribution of *C. rostrata* and *M. trifiliata* distinctly decreased; the content of *Carex elata* increased, and fruitlets of *Oenanthe aquatica* and *Mentha aquatica* appeared. - Aqueous plants: only *A. plantago-aquatica.* occurred	Taxa associated with organic bottom and tolerant for the high trophy appear through the whole core depth.	- Slight increase of cultivated plants (*Secale cereal, Triticum* type) and reduction of ruderals and weeds pollen. - Only single pollen of aquatic and reedswamp taxa are noted. - Spores of *Glomus* are present.

characteristic or diagnostic taxa in the zone. Zone boundaries were determined on the basis of the appearance, disappearance, strong increase, or strong decrease in the number of taxa having a significant quantitative or indicative value.

Diatoms were present only between 135 and 93 cm of the core. A total of 149 diatom taxa were identified in the analysed samples. The detailed analysis of samples shows that the contribution of taxa in particular samples is not uniform, and varied from 32 to 53. There were samples with the highest diversity index, which varied between 2.74 and 3.45. Diatoms analysis of deposits indicates two main stages of environmental development: D1 and D2 (Fig. 9) with no diatoms in the D2 stage and three subzones in the D1 stage – D1a, D1b, D1c (Table 3). The lowest diatom diversity among all of the samples (Shannon-Weaver index = 2.74) was observed at the top of D1 phase. Tychoplanktonic (random planktonic) forms dominated. The contributions of tychoplanktonic species (e. g. *Cocconeis placentula* var. *lineata, Staurosira construens, Pseudostaurosira brevistriata, Epithemia turgida*) were relatively high (from 65.2 until 92.2% relative abundance). The abundance of planktonic species was rather low, from 1.6 until 34.8%. Planktonic species included *Ellerbeckia arenaria* and *Aulacoseira granulata* (Fig. 9). The reconstruction of pH (7.3–8.3) showed that environment was slightly alkaline.

The sediments contain 20 **Cladocera** species, belonging to 3 families: Bosminidae, Daphniidae, and Chydoridae (Fig. 10). Four local cladoceran assemblage zones (LCAZ) were distinguished (Table 3).

From the sequence, 2488 head capsules of **Chironomidae** were recovered and identified to 83 morphospecies. Ceratopogonidae specimens were identified to the family level (Fig. 11). Three significant phases of moat community development were distinguished (Table 3). Trophic status reconstruction based on the British training set indicates a state of almost permanent hypertrophy (Fig. 12). The concentration of total phosphorous only a few times dropped below 100 μg TP/l (at 115–119, 107, 99, 67 and 59 cm). Because at 79 cm (ca. 1550 AD) the reconstructed trophic condition even exceeds 200 μg TP/l, the amplitude is large (128.25 μg TP/l). However, a few species recorded from the samples are not included in the modern British training set, which may limit the reliability of that reconstruction. Lower, although still relatively high trophic conditions are inferred from the reconstruction based on the Finnish model. This model indicates more stable eutrophic conditions (37.8–68.9 μg TP/l) with an increasing trend. This trend is the most visible from 103 to 75 cm (2nd half of 15th – 16th c. AD), which is the section of high eutrophication, with the peak at 79 cm (68.94 μg TP/l). The second peak is recorded at 63 cm (1st half of 17th c. AD) (68.94 μg TP/l), but also deeper (115–119 cm and 127 cm) the trophic condition exceeds 50 μg TP/l. The lowest trophic condition (37.84–41.17 μg TP/l) is recorded at the beginning of Ch1 phase and in the end of Ch2 phase (135 and 59-55 cm).

Only four fossil assemblages contained sufficient identified taxa of **beetles** to allow even a cursory palaeoenvironmental reconstruction, as follows (Tables 3 and 4). The sample from 78 to 76 cm showed clear indications of standing, well-vegetated water with possibly mosses, sedges and accumulations of plant detritus along the margins, based on the presence of the predaceous diving beetle *Graphoderus*, the water scavenger beetle, *Coelostoma orbiculare*, and the marsh beetle genus *Cyphon*. There is also clear evidence of herbivore dung on the nearby landscape. The dung beetle genus *Aphodius* contains many species that feed on cow, horse, and sheep dung.

Sample Level 56-50 cm from contained fossils of the minute moss beetle family. *Hydraena riparia*lives in overgrown, stream-fed, whereas *Helophorus* lives mainly in small ponds with muddy bottoms.

The results of the beetle and caddisfly fossil study of samples from 78 to 46 cm, from the second half of the 16th century to the 19th century, are reported in Table 3.

Ordination analysis. Generally DCA axis 1 of pollen, plant macrofossils and chironomids reveal similar trends: high SD values in the

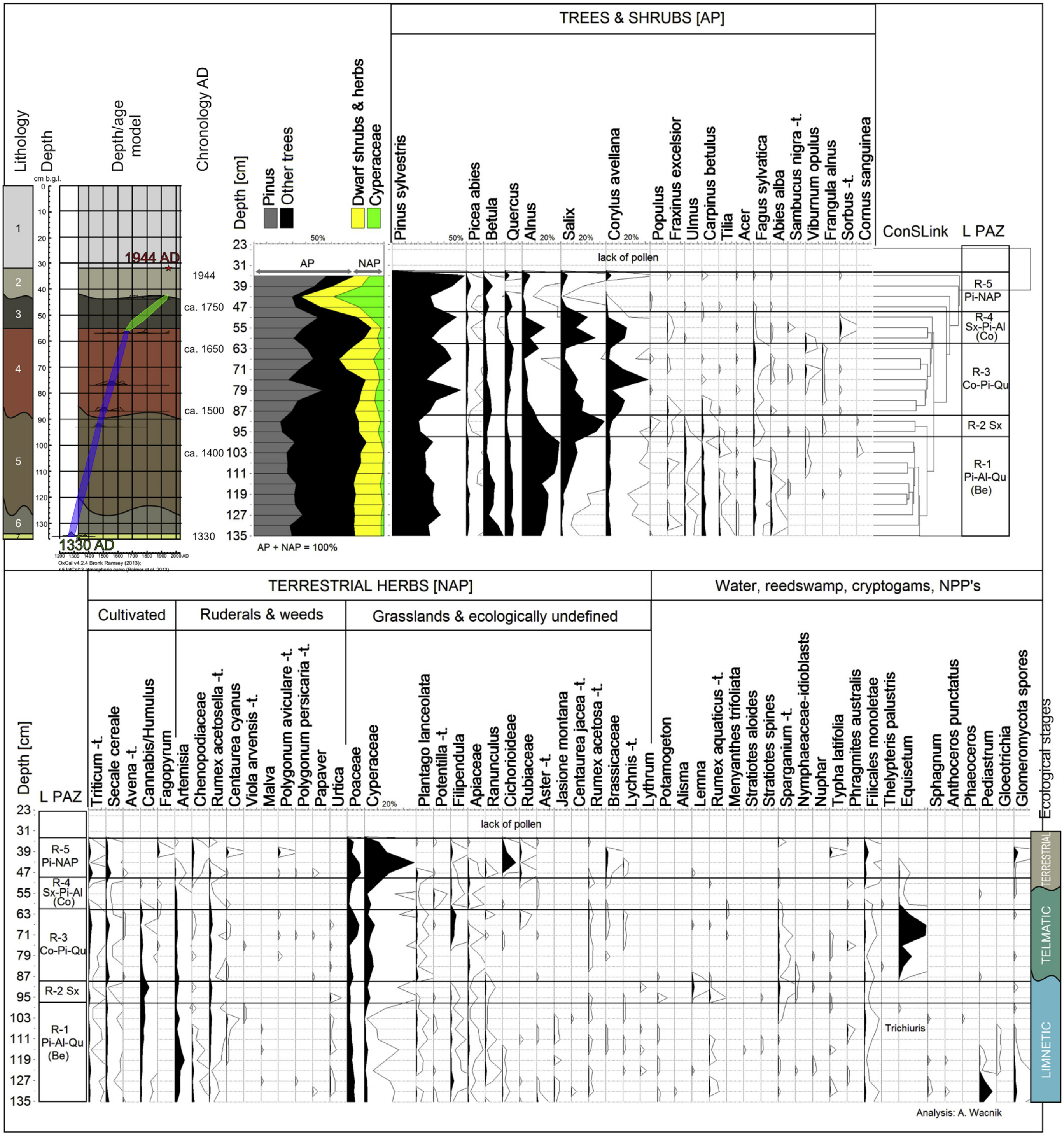


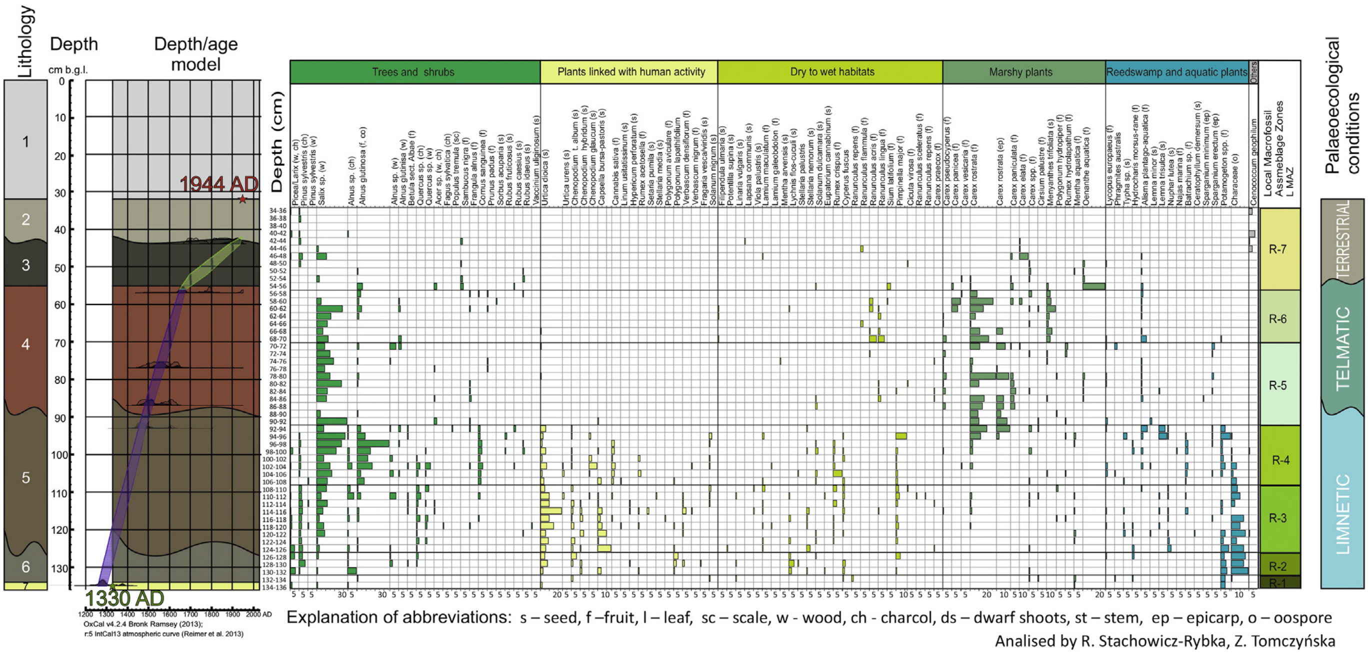
Fig. 7. Percentage pollen diagram with selected taxa of trees and herbs from core RP W3 O2 (analysis by A. Wacnik).

limnetic phase, a decreasing trend in the telmatic phase, and a sharp decline during the terrestrial phase. Diatoms decline continuously from high values in lithological unit 6 to the disappearance in the end of limnetic phase. Cladocera variation is high in lithological units 6 and 4 followed by a decline in scores in lithological units 5 and 3. The first PCA axis of geochemical variables reveals two peaks at the lithological unit 6/5 transition and in lithological unit 3 (Fig. 13).

5. Discussion

5.1. *Transformations of local vegetation reflected in the sediments of the moat fill*

The moat habitat underwent a series of transformations since its formation in the Late Middle Ages (ca. 1330 AD), as reflected in the palaeoecological analyses results (Fig. 14). Palaeobotanical results recorded the several stages in development of both terrestrial and swamp/water vegetation on-site and in the immediate vicinity of the



Explanation of abbreviations: s – seed, f –fruit, l – leaf, sc – scale, w - wood, ch - charcol, ds – dwarf shoots, st – stem, ep – epicarp, o – oospore

Analised by R. Stachowicz-Rybka, Z. Tomczyńska

Fig. 8. Diagram of selected plant macrofossils for the main moat fill from core RP W3 O2; full data available in Suplementary Data Table 1. (analysis by R. Stachowicz-Rybka).

stronghold at Rozprza during ca. four centuries, from the digging of the moat in the Late Medieval period until its complete overgrowth by plants and in-filling with sediments in Modern times. Due to the very small size of the water reservoir (up to 20 m wide and ca. 1.0–1.5 m deep) not only the carpological but also the palynological sequence demonstrates the highly local aspect of vegetation changes (eg. Prentice, 1985).

5.1.1. Stage 1 (L PAZ R 1–2; L MAZ R 1–4; ca. 1330-15th c. AD)

From the very beginning of the moat's existence, the surroundings were partly open, perhaps with more substantial areas of woodland at some distance from the site (Fig. 7). Pine woods and/or mixed pine-oak woods, with admixture of birch and spruce, similar to the present Querco-Pinetum and Leucobryo-Pinetum associations, may have grown on drier upland habitats. Patches of deciduous woodlands with hornbeam, oak, single stands of lime, maple, hazel and elm in the type of Tilio-Carpinetum, occurred at a distance. The wetter surfaces were overgrown by alder woods in the type of Carici elongatae - Alnetum with domination of *Alnus glutinosa* and admixture of birch, alder buckthorn and single ash as well as patches of willow carr.

Palynological observations showed that values greater than 10% confirm the local presence of *Alnus* at the site (Lisitsyna et al., 2011; Douda et al., 2014). Alder is a high pollen producer in the early spring. As pollen grains can be spread by wind far from the flowering trees, quite numerous findings of fruits, charcoal and wood particles in the moat sediments were important indicators confirming its local presence. According to Szymczyk (2015) alder seeds are dispersed effectively by water, while wind dispersal is commonly limited to the vicinity of the tree. Both the values of alder pollen (10–28%; L PAZ R 1–2, Fig. 7) as well as macrofossils (L MAZ 1–4; Fig. 8) deposited in a very small water basin (i.e., the moat), suggests that stands of alder trees were probably growing within several dozen to several hundred meters from the studied moat (see sampling point marked on Fig. 14.1). The role of alder diminished in the 2nd half of the 15th c. AD while the local representation of *Salix* increased. Willows grew a small distance from the moat, as confirmed by macrofossils noted from the beginning of the moat existence, as well as pollen. However, the highest pollen values of *Salix* at the end of the 15th c. AD suggest that willow trees or shrubs

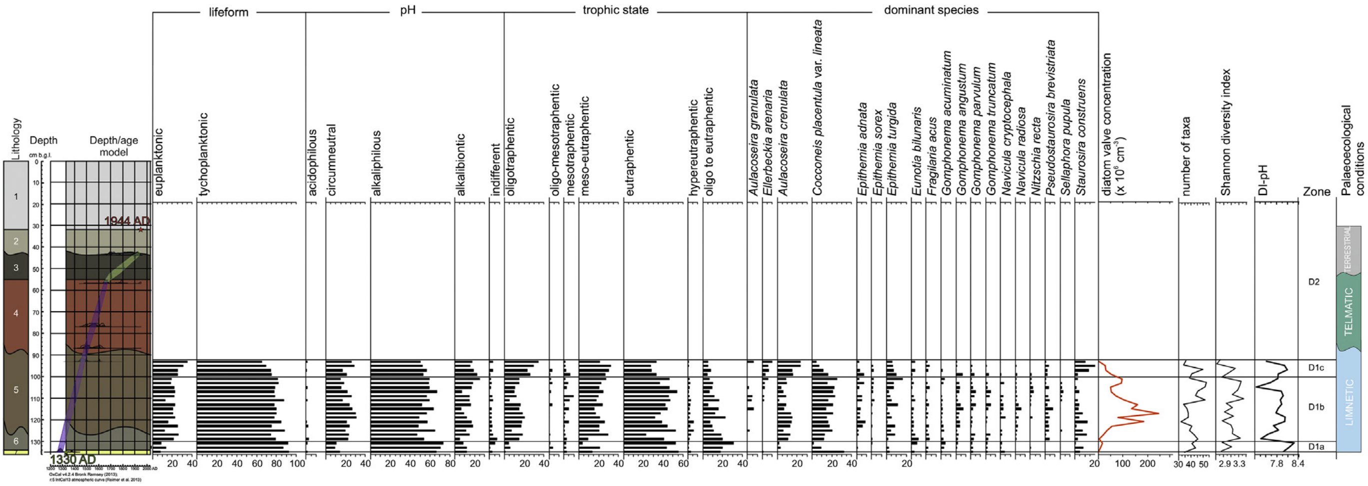


Fig. 9. Percentage Diatom diagram for the main moat fill from core RP W3 O2 (analysis by M. Rzodkiewicz).

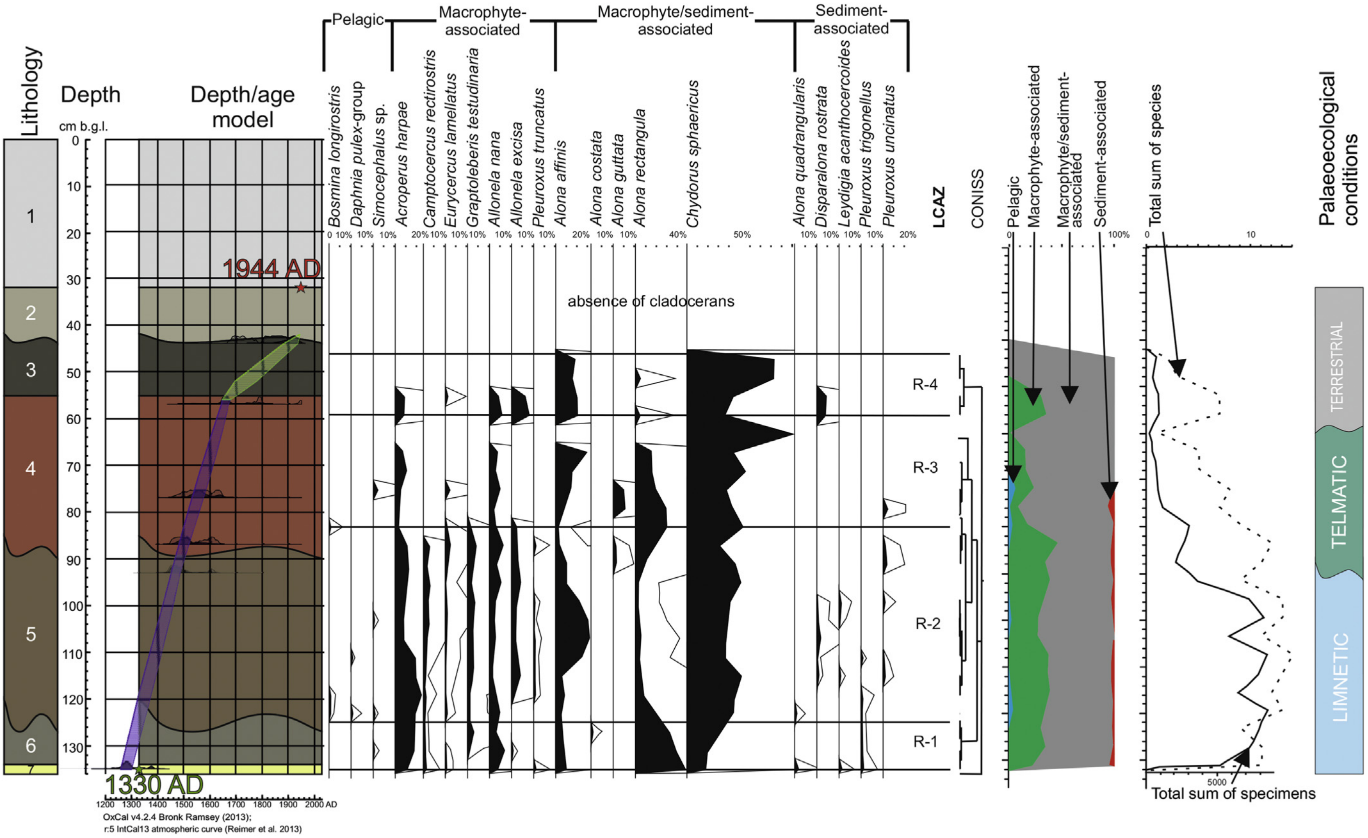


Fig. 10. Percentage Cladocera diagram for the main moat fill from core RP W3 O2 (analysis by D. Pawłowski).

grew closer to the sampling site or the surface occupied by carrs increased during that time (this short-lasting phenomenon was not marked on Fig. 14.1).

Agricultural activities conducted in the immediate vicinity of the site are confirmed by the remains of cereals, hemp and/or hop, flax, as well as weeds of arable fields (eg. *Centaurea cyanus*, *Viola arvensis*).

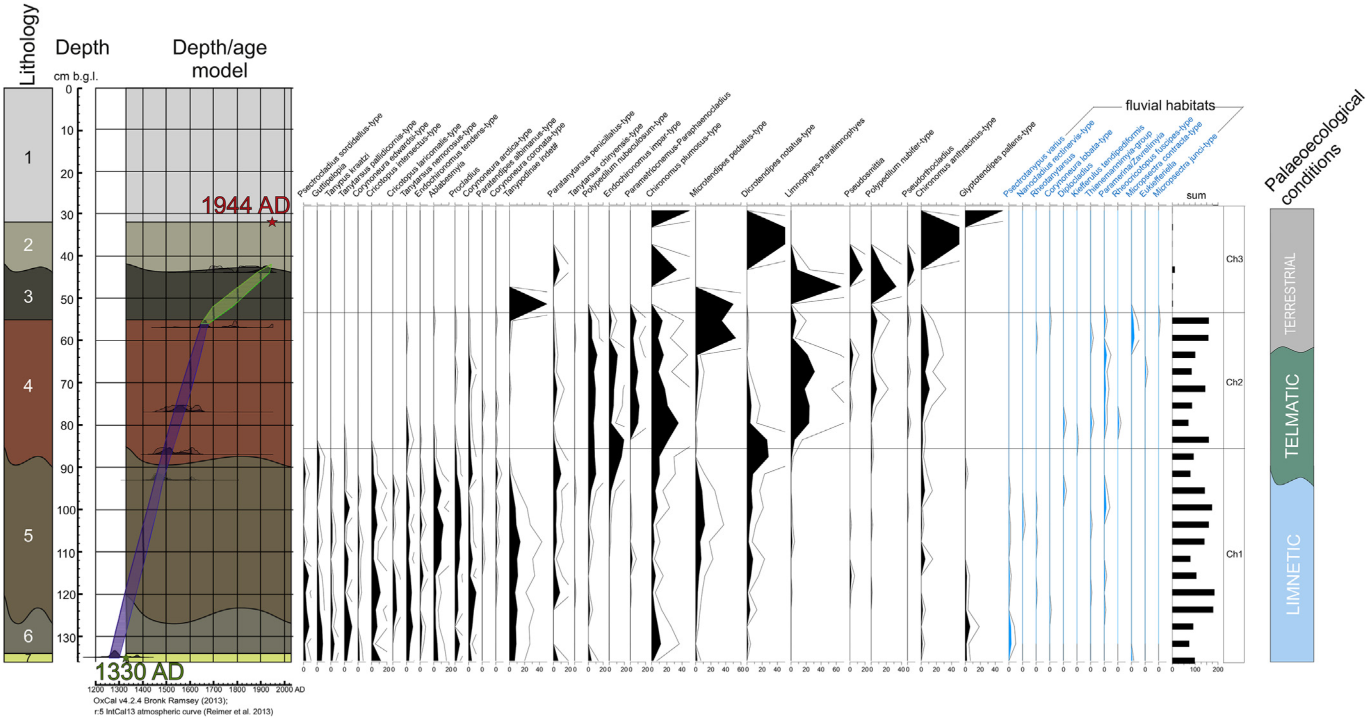


Fig. 11. Percentage Chironomidae diagram (selected taxa) for the main moat fill from core RP W3 O2; full data available in Suplementary Data Table 2 (analysis by O. Antczak).

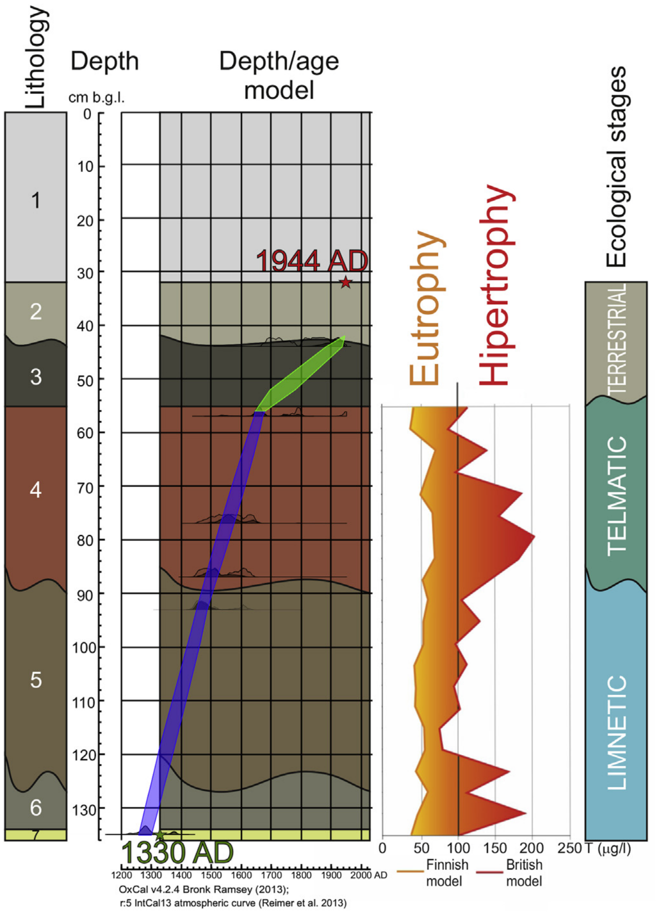


Fig. 12. Palaeoecology and macrohabitat reconstruction for the main moat of the Rozprza motte based on Chironomidae analysis diagram from core RP W3 O2 (analysis by O. Antczak, S. Brooks, T. Luoto, M. Płóciennik).

Although the presence of over a dozen fruits of hemp (*Cannabis sativa*) and seeds of flax (*Linum usitatissimum*) (Fig. 8) suggests that the moat could have been occasionally used as a rettery. However, low values of *Cannabis/Humulus* type pollen (below 5%) do not support this reconstruction (Kittel et al., 2014). Nevertheless, the macrofossil evidence provides good confirmation of local cultivation of these two taxa. Similar observations were made by the results of excavations conducted in nearby palaeochannels, where relicts of retteries were found (Kittel et al., 2018). Remains of hemp and flax were accompanied at Rozprza by seeds of alder buckthorn (*Frangula alnus*). Its local growth was registered also in the pollen record. Seeds and bark of this shrub were commonly used for dyeing textiles. At this time, numerous plant taxa related to human activity grew close to the moat. Remains of weeds accompanying the cultivation of grains, and bulb and root plants, have also been identified, such as *Capsella bursa-pastoris*, described from a bundle of flax (Latałowa, 1998). Local economic activity is also shown by relatively numerous anthropogenic indicators such as the weed species: *Setaria pumila*, *Rumex acetosella*, *Stelaria graminea*, *S. media*, *Chenopodium* t. *album*, *Ch. hybridum*, *Setaria pumila*, *Polygonum aviculare*, *P. lapathifolium* and *Urtica urens* (Lityńska-Zając, 2005). The surrounding meadows were pastures for farm animals. More elevated, drier habitats were covered by eg. *Plantago lanceolata*, *Verbascum densiflorum*, *V. nigrum* and *Hypericum perforatum*, known from many medieval sites.

Disturbed ruderal habitats and fallow lands near the motte were suitable for *Artemisia*, *Urtica dioica*, Chenopodiaceae, *Rumex acetosella* and *Malva* growth as well as for the hornworts *Anthoceros punctatus* and *Phaeoceros laevis*. The shores of the moat were evidently overgrown by alder but grasslands occurred nearby. The characteristic vegetation for this stage was quite high taxonomic diversity of the grassland taxa. The extent of open communities in the pollen record was partly masked by the high proportion of pollen of wind-pollinating trees, such as *Pinus*, *Quercus*, *Alnus*, *Betula,* which are high pollen producers (Broström et al., 2008; Baker et al., 2016). The results obtained by different authors from the reconstruction of past landscape openness based on different reconstruction models (LRA and LOVE, REVEALS, eg. Sugita, 2007) revealed, that the relationship between plant percentage-cover and the pollen percentages is different for different taxa. The plant percentage-cover is usually higher than the pollen percentages, for example in the case of *Picea*, *Tilia*, *Fagus*, Poaceae, Cerealia, Cyperaceae, *Rumex* in contrast to *Pinus, Quercus, Alnus* and *Betula* when this relationship is lower (eg. Gaillard et al., 2010).

The moat margins were overgrown by numerous herbaceous plants representing rush communities such as Cyperaceae, *Typha* sp., *Phragmites australis, Rumex aquaticus*, *Sphagnum*, and *Juncus* sp. Both *Alisma plantago-aquatica* and *Typha* sp. are typical components of the bulrush community. When the moat was functioning as a water basin (mainly in the 14th c.), the water infilling the moat was clear and rich in calcium carbonate, as shown by the presence of numerous Characeae oospores. Simultaneously, eutrophication and nitrogen content rose on the moat margins. In the 14th and 15th c. AD; (L MAZ R 3–4), numerous taxa of aquatic plants grew in the area, such as *Potamogeton friesii*, *P. pusillus*, *P. natans*, *Nuphar lutea*, *Sparganium microcarpum*, *Alisma plantago-aquatica*, *Lemna trisulca*, *L. minor* and *Batrachium* sp. The reservoir's water surface was probably covered by a Lemnatea type pleustone community with *Lemna trisulca* and *L. minor* as its main components (Matuszkiewicz, 2001). Various species of *Potamogeton* sp. occurred in the water column. In shallower places, *Hydrocharis morsus-ranae* and *Stratiotes aloides* grew on a muddy bottom. The water body contained green and blue algae, eg. *Pediastrum*, Characeae (oospores), and *Gloeotrichia* and was contaminated with whipworm parasites (*Trichiuris*).

The regular presence of Glomeromycota spores in the bottom part of the deposits can be related to the erosion and the supply of allochthonous matter to the basin. Due to the small size of the moat, it cannot be excluded that these spores originated from fungi that colonized the roots of the plants overgrowing the shores. According to Kołaczek et al. (2013) spores of arbuscular mycorrhizal fungi are considered to be a reliable indicator of erosion, but only in lacustrine deposits without peat interbedding.

5.1.2. Stage 2 (L PAZ R 3, L MAZ R 5; 16th - 1st half of 17th c. AD)

A strong reduction of *Salix* from the beginning of the 16th c. AD (87 cm) and subsequent expansion of *Corylus avellana* can be ascribed to drying habitat conditions. The higher frequency of *Corylus* (L PAZ R 3) and the regular presence of *Cornus sanguinea*, *Frangula alnus*, *Viburnum opulus, Euonymus* and *Sorbus* illustrate a local development of thickets. Patches of pine woodland with admixture of oak and single birch persisted at some distance from the moat, and possibly gained slightly in importance in the late 16th c.

Representation of cereals, *Cannabis/Humulus* and *Fagopyrum*, as well as the weeds *Artemisia*, *Rumex acetosella*, *Centaurea cyanus*, Chenopodiaceae, *Polygonum aviculare*, *P. persicaria*, *Viola arvensis*, and *Spergula*, confirm the continuation of local cultivation in 16th – 1st half of 17th c. AD. In the same period, meadows and pastures could also have been a more important component of the local environment. This is marked in the pollen record eg. by higher frequencies of Poaceae, *Plantago lanceolata*, *Filipendula*, and *Rumex acetosa*.

From ca. 1500 AD, a decline in water levels resulted in the retreat of aquatic plant communities, which were responsible for the formation of coarse detritus gyttja. With time, the moat was gradually infilled with organic sediments and became shallower, and transformed into swamp with peat accumulation. With the decrease of water level, diatoms disappeared from the sediments. The diatom analysis indicates two

Table 4
Stratigraphy of Coleoptera and other insect subfossils of deposits from the RP W3 O2 core at Rozprza site (analysis by S. Elias).

Taxon	Depth (cm)													
	46–48	50–52	54–56	62–64	70–72	76–78	78–80	82–86	90–92	98–100	102–106	114–116	118–120	122–124
COLEOPTERA														
Dytiscidae														
Graphoderus sp.						1								
Carabidae														
Trechus rubens (Fab.)	1				1									
Helophoridae														
Helophorus sp.		1												
Hydraenidae														
Hydraena riparia Kugl.		1	1											
Hydrophilidae														
Coelostoma orbiculare (Fab.)						1								
Staphlinidae														
Arpedium quadrum (Grav.)	1													
Lathrobium sp.		1							1					
Stenus spp.		1		1							1			
Heterothops dissimilis (Grav.)										1				
Atheta sp.						1	1							
Scirtidae														
Cyphon sp.						1						1		
Elateridae														
Lacon sp.	1													
Scarabaeidae														
Aphodius sp.						1								
TRICHOPTERA														
Limnephilidae														
Genus & species indet.			1			1		1	1					1
Molannidae														
Molanna sp.													1	

stages of environmental development. The first phase, in 14th and 15th c. AD, includes a large amount of mostly eutrophic and benthic diatoms. The second phase, from the peat layer (after ca. 1500 AD), is characterized by the disappearance of diatoms (Fig. 9).

Gradually (in the 15th/16th c. transition L MAZ R 4/5) the reservoir surface became overgrown, mainly by *Carex rostrata*. The communities included also *Carex praecox*, *C. pseudocyperus*, *C. paniculata* and *Menyanthes trifiliata*. Accumulation of sedge peat began, with *Carex rostrata* as the dominating component of the peat land forming bulrush. Development of these communities often causes a drying of standing waters. The abundance of *Carex rostrata* fragments distinctly decreased at 84-82 cm (ca. 1530 AD) and 78-72 cm (ca. 1580 AD), and at the same time the remains of aquatic plants such as *Sparganium erectum*, *S. minimum* and *Lemna trisulca* occured. This may indicate a periodic increase in water level, causing temporary infilling of the remaining moat by standing water.

This phenomenon is clearly marked, not only in the carpological but also in palynological record. In the mid-16th c. (from 83 cm) high

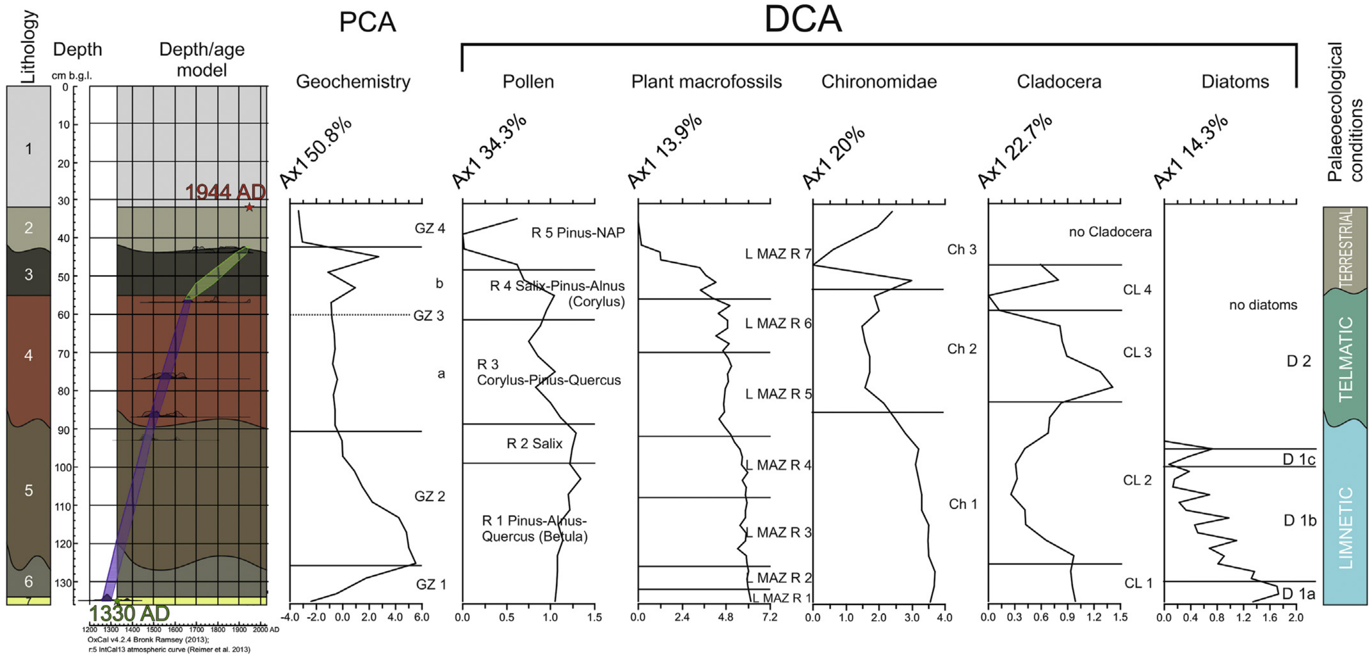


Fig. 13. PCA and DCA diagram for the main moat fill from core RP W3 O2 (prepared and editing by M. Płóciennik).

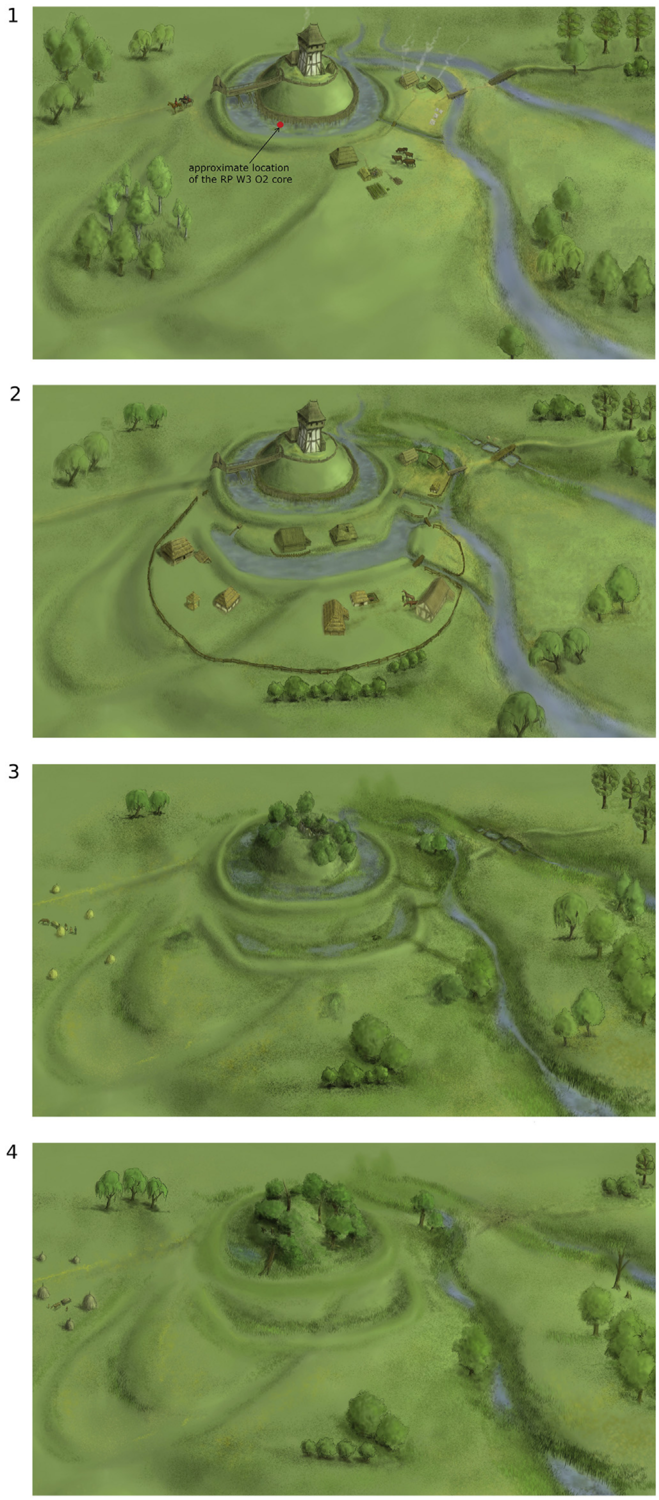


Fig. 14. Phases of the evolution of the main moat of the Rozprza motte-and-bailey (editing by J. Sikora & A. Wacnik).
1 – ca. 1330 AD – ca. 1400 AD; 2 – ca. 1400 AD – ca. 1500 AD; 3 – ca. 1500 AD – ca. 1700 AD; 4 – ca. 1700 AD – 1944 AD.

values of *Equisetum* spores suggest that probably *E. fluviatile* (characteristic of current *Equisetetum fluviatilis* association) was the most important component of shallow water/swamp communities. In such a community *Potamogeton*, *Stratiotes aloides*, *Lemna*, *Nuphar*, Nymphaeaceae, *Sparganium*, *Typha*, *Rumex aquaticus*, *Phragmites*, *Menyanthes* and Cyperaceae, represented by pollen and other microremains, could have grown.

5.1.3. Stage 3 (L PAZ R 4, L MAZ R 6; 2nd half of 17th – 1st half of 18th c. AD)

Subsequently the palynological record indicates a short-lived spread of hazel thickets, with willows and alder in wetter habitats (L PAZ R 4, 2nd half of 17th c. – 1st half of 18th c. AD) synchronous with the reduction of human indicators. Cultivated fields were still present in the area, although with a lower frequency of *Secale cereale*, *Triticum* type, *Cannabis/Humulus* pollen as well as weeds, suggesting a temporary decline of agriculture. Some surfaces were constantly used as meadows and pastures.

The margins of the moat in the succeeding L MAZ R 6 (17th c. AD), became overgrown by various tree species, such as *Prunus padus*, *Frangula alnus*, *Cornus sanguinea*, *Sorbus acuparia* and *Rubus idaeus*, which can be used for consumption or as medication. *Ranunclus acris*, *R. flammula*, *R. lingua* and *Sium latifolium* grew on waterlogged meadows, together with Poaceae, *Filipendula*, and *Lychnis*.

Magnocaricion communities could have been common in the area. The moat surface was dominated by *Carex panicea*, C. *pseudocyperus* and *Menyanthes trifiliata, Phragmites*, *Sparganium* and/or *Typha angustifolia*.

5.1.4. Stage 4 (L PAZ R 5, L MAZ R 7; 2nd half of 18th – 1st half of 20th c. AD)

At least the upper part of the profile, within overbank alluvia, contains hiatuses and the biological record is therefore fragmentary. The low abundance of plant macrofossils in the last phase of moat's existence, from the 18th to 1st half of 20th c. AD, may on the one hand have been the result of seasonal water level oscillations (floods), and on the other hand, to a gradual infilling of the depression by overbank deposits. In this period, *Cenococcum geophilum*, a ubiquitous ectomycorrhizal fungus living on, in, or just below the litter horizon (eg. Thormann et al., 1999), was detected in high abundance. The record of its sclerotia could indicate that organic matter in surface soil was eroded and deposited in the moat (Wick et al., 2003).

The palynological record showed a predominance of pine pollen and a strong reduction in all remaining arboreal taxa, which can be interpreted as a sign of a more open environment. In the Rozprza area, scattered pine woods with oak and birch may have existed. Agricultural activity slightly increased in the area and *Triticum*, *Secale cereale* and *Fagopyrum* were among cultivated taxa. Extensive areas were covered by meadows, mostly overgrown by Cyperaceae, Poaceae, Cichorioideae, Rubiaceae and *Filipendula*.

The character of the depression suggests that the moat surface was gradually transformed in a waterlogged meadow, overgrown with *Lapsana communis*, *Lamium maculatum*, *Solanum dulcamara*, *Rananculus flammula* and *Sium latifolium*.

5.2. Ecological-faunistic characteristic of the moat basin

The DCA axis 1 scores of cladocerans assemblages suggest that they responded to local habitat change such as decreasing water level and material/nutrient input in the moat. The decrease in DCA Axis 1 scores of cladocerans and diatoms until ca. 107 cm coincides with the highest values of the PC Axis 1 scores of the geochemical composition (Fig. 13). The increasing trend in PC Axis 1 indicates the enhanced accumulation of fine-grained inorganic material. Cladocera and diatoms responded faster to water level changes, material and nutrient input than chironomids. Planktonic organisms are sensitive to changes in water transparency (as a result of pollution and eutrophication), while local plants (macrofossils) and benthic chironomid assemblages responded weakly to this factor. This was connected to repeated water level changes, which were most likely associated with an increase in the activity of the Luciąża River. A similar trend has been widely observed in other oxbow lakes and mires throughout Central Poland (Pawłowski et al., 2016).

Plant communities (pollen, macrofossils) and chironomids show different pattern in terms of DCA axis 1 scores, from high to low Axis 1 [SD values]. They may reflect mainly changes in moat and motte macrohabitat. The settled phase of the motte is reflected in high Axis 1 [SD units] scores during R1, R2 (pollen assemblages). At the same time (L MAZ R1-4, Ch 1) the moat was maintained by settlers in a limnetic state. Decrease of Axis 1 scores at ca. 16th-18th c. (R3, R4; L MAZ R 5–6, Ch 2) possibly reflects the abandoned stage of the motte and the telmatic phase of the moat. This was associated with an expansion of non-cultivated and forest taxa (pollen), a decrease of domestic and ruderal plants, replacement of aquatic taxa by telmatic taxa (macrofossils) and a decline in chironomid diversity. Finally, the terrestrial phase of the moat in the 19th-20th c. revealed poor preservation or near absence of midge and plant macrofossils and changes in pollen communities due to landscape transformation associated with economic changes in the region.

Both the composition of the plant macrofossils and the sediment type – gyttja with sand admixture, suggest a highly dynamic environment and indicate that during the initial phase of moat functioning, the sediments in the very bottom of the moat may have been reworked. However, water infilling the moat was clear and rich in calcium carbonate, probably from the older cultural layers cut to form the moat's ditch. The rapid increase in $CaCO_3$ content (up to nearly 30% at the depth between 128 and 122 cm) resulted not only from the presence of calcium bicarbonate in waters but also from biogenic decalcification of the lake waters caused by a large biomass of aquatic macrophytic nature. The occurrence remains of Characaceae, and of *Chara* seems in particular, to the 2 m depth interval, indicate conditions that were optimal for the production of biomass and the precipitation of $CaCO_3$ (Pełechaty et al., 2013). Good oxygenation of waters during sedimentation of coarse detritus gyttja is indicated by a low value of Fe/Mn (mean values not exceeding 33) and a low organic matter content (mean value of LOI not greater than 24%), which is caused by rapid decomposition of organic remains. The changes observed between 118 and 99 cm (2nd half of 14th c. – 1st half of 15th c. AD) with macrofossils of hemp and flax may indicate that the moat was used as a rettery, although this interpretation is not supported by the pollen evidence. This partly explains the presence of littoral cladocerans, such as *A. rectangula*, *D. rostrata*, *L. acantocercoides*, and *Ch. sphaericus*, which prefer more eutrophic, turbid water, and reflects a response to the influx of nutrients to the moat as a result of the inundations of flood waters or pollution and eutrophication caused by the primitive technology of hemp fibre production. Such conditions might have led to the disappearance of zooplankton and diatoms through decreased access to the light (Damme van et al., 2009). In turn, the periodic appearance of planktonic cladocerans may indicate periods of increased water transparency due to periodic flooding or flowing/rinsing and consequent changes in the nutrient load. Low values of *Cannabis/Humulus* type pollen within the moat fill deposits appears to exclude the use of the moat as a rettery, however water from surrounding retteries could enter the feature during rinsing (flushing) of the ditch.

The frequency and diversity of Cladocera (Fig. 10) includes a large number of benthic taxa, of which some are important indicators of eutrophic water (*A. rectangula, Ch. sphaericus L. acanthorecoides*, and *B. longirostris*) and rich vegetation in the shallow moat (*A. affinis, A. guttata, Ac. harpae, G. testudinaria, E. lamellatus*, genus *Pleuroxus*). Additionally, a relative increase in frequency of sediment-associated cladocerans and those taxa (eg. *Ch. sphaericus*, *A. affinis*, *A. harpae* and *D. rostrata*) that can tolerate changes in hydrological conditions may indicate turbid water conditions (Pawłowski et al., 2015a, 2015b). These observations are also confirmed by decreasing values of LOI in the deposits. Stratigraphic changes in LOI, inorganic and calcium carbonate content are very closely connected with the lithology of the deposits. Based on lithostratigraphy, three organic-rich zones and three mineral-rich zones were distinguished in the profile. This supports the hypothesis of episodic in-wash of sediments from the moat banks. A decrease of frequency of Cladocera also indicates deteriorating conditions at the end of this phase (59 cm). The moat was probably overgrown by macrophytes, as reflected in the composition of Cladocera species that live amongst plants in swamps and mires (Pawłowski et al., 2015a). High chironomid abundance and diversity in the first stage of moat development indicates favourable conditions for Chironomidae, as well as respectively high water level and trophic status (Fig. 12). During almost the whole of the Ch1 stage (136-85 cm core depth; 1330 - ca. 1500 AD) the dominant species are associated with permanent stagnant water partly overgrown by macrophytes, accompanied by the deposition of coarse detritus gyttja. Phytophilous chironomid taxa were not only abundant, but also diverse. The occurrence of mining chironomids corresponds with the presence of certain macrophyte taxa, eg. *Nuphar lutea* co-occurs with *Glyptotendipes pallens*-type and *G. severini*-type. However, *Endochironomus tendens*-type was recorded deeper than *Alisma plantago-aquatica,* which is its host plant (Figs. 8 and 11) (Moller Pillot, 2009, 2013). Another group – bottom dwellers, eg. *Psectrocladius sordidellus*-type 1 and type 2, *Cryptochironomus*, *Glyptotendipes* and *Cricotopus* (Moller Pillot, 2013), inhabited the clayey coarse-detritus gyttja (132-125 cm) and the coarse-detritus gyttja (125-90 cm). The high abundance of predatory Tanypodinae implies the presence of a more complex ecosystem with several trophic levels.

In the Ch2 zone (depth 85-53 cm; ca. 1500 - ca. 1700 AD) taxa richness decreased, but there was still high abundance of Chironomidae. A few semiterrestrial taxa appeared, mostly *Parametriocmenus-Paraphaenocladius* and *Limnophyes-Paralimnophyes.* There are several possible reasons for this: 1) those chironomids inhabited only the telmatic banks of the moat, 2) the moat seasonally desiccated, eg. during summer, or 3) the moat slowly started to paludify and telmatic conditions developed, as confirmed by peat accumulation. In the Ch3 phase (53-32 cm; ca. 1700–1944 AD) a sudden decrease of Chironomidae abundance is observed. Singule head capsules of semiterrestrial taxa (*Limnophyes-Paralimnophyes, Pseudosmittia* and *Pseudorthocladius*) indicate that the moat environment was transformed into limnotelmatic habitat. Nevertheless, some subfossils from Chironomini tribe were also present: *Chironomus anthracinus*-type, *C. plumosus*-type, *Dicrotendipes notatus*-type, *Glyptotendipes pallens*-type, *Microtendipes pedellus*-type and *Polypedilum nubifer*-type (Fig. 8). *Microtendipes pedellus* often occurs in groundwater seepages. All other species occur in the muddy bottoms of backswamp basin, such as developed within the retain ditch of the moat. The chironomid assemblages indicate the existence of seasonal surface water, such as small puddles. The larvae of *Glyptotendipes pallens* are known as leaf miners, but they also can be found on wood and coarse organic matter, abundant in the moat in that time, as confirmed during excavation works.

5.3. Flooding phases in the Luciąża River valley or rinsing of the moat basin?

Previous studies in the Polish Lowalands often document the necessity of removal of early medieval settlements (often ring-forts) from valley floors to the upper parts of valleys and uplands, as a result of palaeohydrological changes mostly in 13th-14th c. AD (eg. Kurnatowski, 1963; Dunin-Wąsowicz, 1974; Goździk, 1982). Our results show the different palaeoenvironmental conditions in the Early and Late Middle Ages transition in Rozprza. The motte occupied a very low hillock of the terrace remnant in the central part of the extensive valley floor of the Luciąża River as late as in the 14th - 15th c. AD. As confirmed by the latest dendrochronological data, in the 16th c., the site was re-developed after a period of withdrawal, probably temporarily, in connection with a military necessity.

The changes in deposition basin ecology – from partly open water with coarse-detritus gyttja to a swamp with peat accumulation – took place most probably ca. 1500 AD. During the limnetic and telmatic stages of moat development, evidence of slope wash of moat sides and rinsing of the ditch by river water has been recorded. The presence of slope wash deposits (coarse-grained sands with organic mud laminations – see Fig. 2) is apparent between and below beams of the wooden construction. The pollen evidence suggests moat desiccation began early in the beginning of 16th c. AD. However, more important changes in the depositional environment happened in the third terrestrial stage, as late as in the 18th and/or 19th c., when the accumulation of overbank silty and sandy organic mud was initiated within the moat ditch (Figs. 12–14). This shows that the Luciąża River valley floor was not as intensely flooded from the 14th to the 17th c. However, small flooding or flushing of the moat basin may have occurred.

The palaeoecological analysis of moat fill indicates shallow stagnant water in the first period of ditch's existence, but there is also scant evidence of water level changes. Seasonal water level oscillations in the shallow water basin are indicated by pollen grain corrosion. Changes in the aquatic community during the Rozprza moat development were associated with high water levels, particularly ca. 123-119 cm (mid-14th c. AD), but also ca.119-99 cm (1st half of 15th c. AD), 91-87 cm (beginning of 16th c. AD), (83?), 79-75 cm (2nd half of 16^{h} c. AD), and 63 (?)/59-53 cm (18th c. AD). Generally, in oxbow lakes or fens, the high sensitivity of the aquatic invertebrates (Cladocera and Chironomidae) to changes in water level permitted the reconstruction of potential flood episodes that occurred in the Luciąża River valley. In particular, the presence of rheophilic chironomid species and also the increase in the proportion of sediment-associated Cladocera, (eg. *Pleuroxus uncinatus*, *Disparalona rostrata*), as well as peaks of pelagic taxa (eg.: *Bosmina longirostris*, *Daphnia pulex*-group), could be closely correlated with floods in the valley (Pawłowski et al., 2012, 2016). Although the subfossils were not numerous, their presence is an unequivocal indicator of running water movement. Head capsules of *Rheotanytarsus*, a typical rheobiontic genus, were found in the Ch1 phase (119-99 cm core depth) and once in the Ch2 phase (59 cm). Single head capsules of *Rheocricotopus fuscipes*-type (79 cm) and *Corynoneura lobata*-type (123 and 55 cm) were also recorded. These chironomids are the most numerous in fast-flowing cool brooks and streams, but also in springs and the upper courses of rivers. Moreover, there were also some rheophilic species in the sediments, such as *Nanocladius rectinervis*-type, *Diplocladius, Micropsectra* and *Eukiefferiella*, but also *Corynoneura coronata*-type and *Thienemannimyia* group (Fig. 11), which only occasionally occur in lakes or pools in temperate European lowlands (Moller Pillot, 2013; Vallenduuk and Moller Pillot, 2007). Additionally, in both the limnetic and telmatic stages of the moat's development, there appeared Chironomidae typical of mineral sediments, eg.: *Paratendipes albimanus*-type, *Psectrocladius sordidellus*-type, *Tanytarsus chinyensis*-type (Andersen et al., 2013; Moller Pillot, 2009, 2013). Their presence partially overlaps with the increased concentration of SiO_2 in the sediment, which may indicate irregular inwash of sand and gravel from the moat banks.

Similarly, inferred increases in the water level (or flooding events) are also based on peaks of planktonic diatoms ca. 115 cm (2nd half of 14th c. AD), 111–109 (ca. 1400 AD) cm and above all ca. 93 cm (the end of 15th c. AD). As reported by Wiklund et al. (2010), the high availability of dissolved silica during floods promotes the appearance of greater biomasses of diatoms in flooded basins. This is partly supported by an increase of SiO_{2biog} (Fig. 6), particularly on ca 130-100 cm (14th - 1st half of 15th c. AD). Note the enrichments in SiO_{2biog} correspond also to the peak of diatom valve concentration, SiO_{2ter} and K. Such situations in natural water bodies attest to higher diatom productivity in the period of enhanced denudation in the catchment (Robinson, 1994).

Significantly increased content of inorganic material, especially SiO_{2ter} and the increase in aluminosilicate-bound elements, such as Na, K, Mg and Fe ca. 130-99 cm (14th - 1st half of 15th c. AD) and 82-70 cm (2nd half of 16th c. AD), could indicate a high intensity of floods, but also runoff and deluvial processes in the catchment area of the moat and the slopes of the feature. These inorganic elements are amongst the most important constituents in biogenic deposits and their increased content may be the result of delivery of allochthonous mineral matter, independent of the natural development of the biogenic accumulation in the moat (Rydelek, 2013). Deforestation causes increased runoff from the catchment and results in higher mobility of clastic particles (Ward et al., 2008). Persistent deforestation is inferred from pollen analysis and by the enhanced amounts of SiO_{2ter} in the moat sediments. As indicated by the high values of Mn concentration, the clastic components mainly came in colloidal suspension (Kabata-Pendias, 2010). Extensive farming, confirmed by pollen data, resulted in the erosion of the morainic plateau around the valley, and much fine sediment was supplied to the valley floor, and then to the moat fill.

Additionally, the hydrological changes described above could also be associated with an increase in precipitation. The increase in $CaCO_3$, Na, Mg and Ca (Fig. 6), ca. 126-99 cm (2nd half of 14th and 1st half of 15th c. AD); 76-72 cm (2nd half of 16th c. AD) and 54-52 cm (1st half of 18th c. AD) may have resulted from chemical weathering, which in turn was the result of an increase in precipitation (Ralska-Jasiewiczowa et al., 2003). The transformation from a limnetic environment to a telmatic habitat took place in the moat abruptly ca. 1500 AD. However, the changes observed from 59 to 53 cm (2nd half of 17th - 1st half of 18th c. AD) could be closely associated with river activity and increase of flowing water, resulted in deposition of overbank alluvia in the topmost part of the profile. Geological evidence of overbank deposition in the moats began as late as the 18th or even in the 19th c. and is supported by lithological changes and the geochemical composition of deposits, expressed as increased content of inorganic components, especially SiO_{2ter} and lithophilic elements such as Na, K and Mg from 52 cm (Fig. 6). The PCA axis 2 scores for geochemical composition shows a positive trend between 52 and 32 cm, i.e. ca. 1700–1944 AD onwards (Fig. 13). Positive values of the second eigenvector reflect the occurrence of products of weathering in the catchment (Na, K, Mg, SiO_{2ter}) which might document the enhanced accumulation of fine-grained clastic material and floods. In turn, the high values of Fe/Mn (above 100 cm) seem to indicate low redox conditions at this site, which might be associated with high groundwater levels from 64 to 52 cm (2nd half 17th – 1st half of 18th c. AD).

There is no geological record of great alluviation in the Luciąża River floodplain in Rozprza from the beginning of the Little Ice Age between the 14th and the 17th c.AD, or the earlier floods were not large enough to pass the outer rampart of the motte. Therefore, another possibility is that the Rozprza moat was periodically connected to Luciąża River channel (eg. by artificial canal) (see Fig. 1B and C). A shallow and eutrophic stagnant moat would be a perfect habitat for mosquito larval development. The recurring flushing of the moat could limit populations of these annoying insects. Our quantitative reconstructions of the trophic status of the water indicate permanent eutrophic (or even hypertrophic) conditions throughout the whole core length. The common practice in the Middle Ages was disposal of wastewater from human settlements directly into the moat (Shin et al., 2009; Antoniou et al., 2016), what was the likely scenario here. The use of the moat as a sewage receiver brought several disadvantages, such as algal blooms and obnoxious smells. If the water in the moat was stagnant, it would have been a perfect habitat for the development of pathogenic microorganisms (Shin et al., 2009) and a breeding zone for mosquitoes (Dahl, 1997). Our trophic reconstruction derived from the British inference model suggests that in the initial stage the moat was characterized by high hypertrophy, which decreased between 119 and 85 cm of core depth (the 2nd half of the 14th – beginning of the 16th c. AD), which may provide evidence of regular cleaning of the moat. Moats were widely used in the defensive system of motte residences (Müller-Wille, 1966; Kenyon, 1990; Durdík, 1996; Higham and Barker, 2004; Aarts, 2007; et al.) and the ditch would have to have been kept in proper condition, in order to be effective for defense. Because of the location of the Rozprza fort on the Luciąża River valley floor, it could have been easily reached through connecting the moat with the river by the canal during times of high water levels. The trophic condition of the waters during the Ch1 stage (120-90 cm, 2nd half of 14th – beginning of

16th c. AD), besides the lowest part of core, was respectively lower, but with an increasing trend. The total phosphorus reached the highest values in Ch2 stage (especially from 83 to 63 cm of core depth, 2nd half of 16th – 1st half of 17th c. AD) when the motte was abandoned and the moat started to paludify. It was during this swampy phase of moat development, with the domination of *Carex* sp. (Fig. 8), when organic matter was decomposed on a larger scale. These trends are visible in the reconstructions derived both in the Finnish and British TP inference models (Fig. 12).

Čerba et al. (2010) stated that Orthocladiinae (especially *Cricotopus sylvestris* gr.) typically dominate in highly eutrophic conditions (exceeding 100 μg TP/l), whereas in Rozprza the chironomid fauna is dominated by Chironomini, with *Cricotopus* reaching maximum abundance of 21.5% at 119 cm. According to Brodersen et al. (2001), *Cricotopus* and *Glyptotendipes* are characteristic of eutrophic and hypertrophic lakes with characeans. These algae were also abundant in Rozprza, particularly in the first phase of moat development (Fig. 12). On the other hand, Saether (1979) listed many chironomids, which are abundant in Rozprza, as species occurring in highly eutrophic habitats (hypertrophy was not considered). The difference between the model reconstructions may result from the TP ranges in the lakes of the training sets. Total Phosphorous in the 44 British lakes used in the training set ranged from 68 to 1162 μg TP/l (mean 282 μg TP/l) in England and from 5 to 1085 μg TP/l (mean 144 μg TP/l) in Wales (Brooks et al., 2001), whereas the maximum TP in the Finnish lakes reached 105 μg/l (mean 20.7 μg TP/l) (Luoto, 2011). The high trophic level in Rozprza moat was undoubtedly associated with human impact.

The co-occurrence of taxa, which in lowland areas are associated with clean flowing waters, such as *Chaeotocladius*, *Eukiefferiella*, *Micropsectra*, *Thienemannimyia* agg., or rheobionts (*Rheotanytarsus*) with species living in heavily polluted stagnant waters may also be evidence of a Luciąża River flooding the Rozprza moat or a permanent connection to the river by an artificial canal. Mixed insect assemblages containing opposing ecological groups have been earlier previously as a signal of high energy hydrological conditions (Smith and Howard, 2004).

Water bodies surrounding crannogs were similar in function (but not in origin) to moats (Shelley, 2013). The subfossil chironomid assemblage from the immediate vicinity of the Ballywillin Crannog in Ireland (Ruiz et al., 2006) includes many of the same species found in Rozprza moat. The total phosphorus reconstruction, based on model of Brooks et al. (2001), indicated eutrophy, reaching hypertrophy (up to 230 μg TP/l) in the two last stages. These stages were characterized by a decrease in the number and a shift in the composition of Chironomidae. When *Cricotopus sylvestris*-type, *Microtendipes pedellus*-type and *Glyptotendipes* started to dominate, a large proportion of *Polypedilum nubeculosum*-type persisted. All these species, except *C. sylvestris*-type, were recorded in Rozprza moat, but in the Ch3 phase of moat development there was a clear domination of semiterrestrial species, not seen in the crannog sediments. In Ballywillin, local shallowing was caused by organic deposits from the crannog (Ruiz et al., 2006), whereas we infer that Rozprza was subject to systematic desiccation. However, the cause of local pollution was probably similar in both locations: an intensification of human activity resulting in nutrient enrichment of the water (Ruiz et al., 2006).

It seems that Rozprza moat may have been more influenced by human activities than by natural (flooding) events. For this reason we do not have sufficient data to allow us to plausibly discuss the climatic context of the activity of the Luciąża River - human impacts may obscure climate reconstructions.

6. Conclusion

The Rozprza motte-and-bailey residence was situated in a defensive location on a low sandy terrace remnant in the central part of a partly swampy valley floor of the small Luciąża River. The fortress was inhabited from the 20s-30s of 14th to the 15th c. AD. Based mostly on the dendrochronological data and a series of radiocarbon dates, the depth/age model and also on archaeological artefacts, we estimate the moat was established by 1330 AD.

The palaeoecological analyses indicate the three main stages of moat habitat development. The first stage overlaps with the period of human occupation of the residence (ca. 1330 AD – ca. 1500 AD). The moat was permanently filled with shallow, eutrophic water and over time became partly overgrown with macrophytes. The deposition of coarse detritus gyttja took place in this stage. In a later period of the limnetic stage, presence of hemp fruits and flax seeds indicates that the moat could be also have been used as a rettery, however this is not confirmed by pollen analysis. Evidence of small floods or rather regular rinsing (flushing) of the moat has been recognised. However the moat was only ca. 1.0–1.5 deep and, together with all the fortification, it did not play an important strategic role in the 14th-15th c. AD as a defensive feature for the province or country, but was more than enough to handle local conflicts. We should also remember the importance of the symbolic meaning of towered and moated fortifications as of knightly seats of power in Middle Ages. Searching other purposes for this feature, we should include two more: it could be used for some branches of local production and it played crucial role in the amelioration of the area of residence, situated in wet conditions of the valley floor.

The trophic condition of the moat basin increased rapidly in the second stage (16th-17th c. AD), when the motte was abandoned and it was transformed into swampy habitat with hypertrophic conditions caused by condensed organic matter decomposition on a larger scale. The swampy phase ended abruptly and in the third phase (from ca. 1700 AD) when the moat environment was transformed into terrestrial habitat affected by floods.

The changes of types of deposition basin, from partly open water with gyttja to swamp with peat, took place ca. 1500 AD. The greatest changes of the depositional environment happened in the 18th-19th c. when the accumulation of overbank organic mud and later silty sandy deposits was initiated within the moat ditches. This shows that the Luciąża River valley floor in Rozprza was not flooded from the 14th to the 17th c. AD. An increase of overbank deposition is recorded from the 18th c. AD.

The results of the multi-proxy palaeoecological analyses of the motte moat fill at Rozprza are essential environmental background for the historical events, but can also be used to complement knowledge about human impact on ecosystems and functioning of artificial aquatic habitats. This multi-disciplinary study also permits reconstruction of the palaeoenvironmental development of the Luciąża River valley floor.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2018.03.026.

References

Aarts, B., 2007. Motte-and-bailey castles of Europe. Some aspects concerning their origin and evolution. Virtus. Bull. Werkgr. Adelsgeschiedenis 15, 37–56.

Andersen, T., Cranston, P.S., Epler, J.H., 2013. Chironomidae of the Holarctic region: keys and diagnoses. Part 1. Larvae. Insect Syst. Evol. Suppl. 66.

Antoniou, G.P., De Feo, G., Han, M., Fardin, F., Tamburrino, A., Khan, S., Tie, F., Reklaityte, I., Kanetaki, E., Zheng, X.Y., Mays, L.W., Angelakis, A.N., 2016. Evolution of toilets worldwide through the millennia. Sustainability 8 (8), 779. http://dx.doi.org/10.3390/su8080779.

Armitage, P.D., Cranston, P.S., Pinder, L.C.V., 1995. The Chironomidae. Biology and Ecology of Non-biting Midges. Chapman & Hall, London.

Baker, A.G., Zimny, M., Keczyński, A., Bhagwat, S.A., Willis, K.J., Latałowa, M., 2016. Pollen productivity estimates from old-growth forest strongly differ from those obtained in cultural landscapes: evidence from the Białowieża National Park, Poland. Holocene 26, 80–92.

Battarbee, R.W., 1986. Diatom analysis. In: Berglund, B.E. (Ed.), Handbook of Holocene Paleoecology and Paleohydrology. John Wiley and Sons ltd., Chichester, pp. 527–570.

Beneš, J., Kaštovský, J., Kočárová, R., Kočár, P., Kubečková, K., Pokorný, P., Starec, P., 2002. Archaeobotany of the Old Prague Town defence system, Czech Republic: archaeology, macro-remains, pollen, and diatoms. Veg. Hist. Archaeobotany 11, 107–120.

Bengtsson, L., Enell, M., 1986. Chemical analysis. In: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley and Sons ltd., Chichester, pp. 423–451.

Bennett, K.D., 1996. Determination of the number of zones in a biostratigraphical sequence. New Phytol. 132, 155–170.

Berglund, B.E., Ralska-Jasiewiczowa, M., 1986. Pollen analysis and pollen diagrams. In: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley and Sons ltd., Chichester, pp. 455–484.

Beug, H.-J., 2004. Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Verlag Dr. Friedrich Pfeil, München.

Bjerring, R., Becares, E., Declerck, S., Gross, E.M., Hansson, L.-A., Kairesalo, T., Nykänen, M., Halkiewicz, A., Kornijów, R., Conde-Porcuna, J.M., Seferlis, M., Noges, T., Moss, B., Amsinck, S.L., Vad Odgaard, B., Jeppesen, E., 2009. Subfossil Cladocera in relation to contemporary environmental variables in 54 Pan-European lakes. Freshw. Biol. 54, 2401–2417.

Brodersen, K.P., Odgaard, B., Vestergaard, O., Anderson, N.J., 2001. Chironomid stratigraphy in the shallow and eutrophic Lake Søbygaard, Denmark: chironomid-Macrophyte co-occurrence. Freshw. Biol. 46, 253–267.

Bronk Ramsey, C., 2008. Deposition models for chronological records. Quat. Sci. Rev. 27 (1–2), 42–60.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51 (1), 337–360.

Brooks, S.J., Bennion, H., Birks, H.J.B., 2001. Tracing lake trophic history with a chironomid-total phosphorus inference model. Freshw. Biol. 46 (4), 513–533.

Brooks, S.J., Langdon, P.G., Heiri, O., 2007. The Identification and Use of Palaearctic Chironomidae Larvae in Palaeoecology. QRA Technical Guide No. 10. Quaternary Research Association, London.

Broström, A., Nielsen, B., Gaillard, M.-J., Hjelle, K., Mazier, F., Binney, H., Bunting, J., Fyfe, R., Meltsov, V., Poska, A., Räsänen, S., Soepboer, W., von Stedingk, H., Suutari, H., Sugita, S., 2008. Pollen productivity estimates of key European plant taxa for quantitative reconstruction of past vegetation: a review. Veg. Hist. Archaeobotany 17 (5), 461–478.

Brown, A., Pluskowski, A.G., 2011. Detecting the environmental impact of the Crusades on a late-medieval (13th-15th century) frontier landscape: palynological analysis from Malbork Castle and hinterland, Northern Poland. J. Archaeol. Sci. 38, 1957–1966.

Cappers, R.T.J., Bekker, R.M., Jans, J.E.A., 2006. Digital Seed Atlas of the Netherlands. Groningen University Library, Groningen, Barkhuis.

Chmielowska, A., 1982. Rozprza we wczesnym i późnym średniowieczu. Prace i Materiały Muzeum Archeologicznego i Etnograficznego w Łodzi. Ser. Archeol. 29, 159–206.

Clarke, K.R., Gorley, R.N., 2006. PRIMER v6: User Manual/Tutorial. PRIMER-E, Plymouth.

Čerba, D., Mihaljevic, Z., Vidakovic, J., 2010. Colonisation of temporary macrophyte substratum by midges (Chironomidae: Diptera). Ann. de Limnol. - Int. J. Limnol. 44, 85–94.

Dahl, C., 1997. Diptera Culicidae, mosquitoes. In: Nilsson, A.N. (Ed.), Aquatic Insects of North Europe. A Taxonomic Handbook. Odonata-Diptera, vol. 2. Apollo Books, Stenstrup, Denmark, pp. 163–186.

Dam van, H., Mertens, A., Sinkeldam, J., 1994. A coded checklist and ecological indicator values of freshwater diatoms from The Netherlands. Neth. J. Aquatic Ecol. 28 (1), 117–133.

Damme van, S., Struyf, E., Maris, T., Cox, T., Meire, P., 2009. Characteristic aspects of the tidal freshwater zone that affect aquatic primary production. In: Barendregt, A., Whigham, D.F., Baldwin, A.H. (Eds.), Tidal Freshwater Wetlands, pp. 123–136.

Dénes, J., 2004. Földhalomvárak az Árpádok királyi udvarhelyein. In: Kovács, G., Szabó, M. (Eds.), "Quasi Liber et Pictura": tanulmányok Kubinyi András hetvenedik születésnapjára. ELTE Régészettudományi Intézet, Budapest, pp. 123–129.

Denys, L., 1991/2. A check-list of the diatoms in the Holocene deposits of the western Belgian coastal plain with a survey of their apparent ecological requirements. Serv. Geol. Belg. 1, 2.

Douda, J., Doudová, J., Drašnarová, A., Kuneš, P., Hadincová, V., Krak, K., Zákravský, P., Mandák, B., 2014. Migration patterns of subgenus *Alnus* in Europe since the Last Glacial maximum: a systematic review. PLoS One 9 (2). http://dx.doi.org/10.1371/journal.pone.0088709. e88709.

Dunin-Wąsowicz, T., 1974. Zmiany w topografii osadnictwa Wielkich Dolin na Niżu Środkowopolskim w XIII w. Ossolineum, Wrocław.

Durdík, T., 1996. Encyklopedie českých hradů. Nakladatelství Librí, Praha.

Elias, S.A., 2010. Advances in Quaternary Entomology. Developments in Quaternary Sciences. Elsevier, pp. 12.

Elias, S.A., 2015. second ed. Overview of Fossil Beetles. Reference Module in Earth Systems and Environmental Sciences. Encyclopedia of Quaternary Science, vol. 2013. pp. 161–172.

Folk, R., Ward, W., 1957. Brazos River bar: a study in the significance of grain size parameters. J. Sediment. Petrol. 27 (1), 3–26.

Frey, D.G., 1986. Cladocera analysis. In: Berglund, B.E. (Ed.), Handbook of Holocene Paleoecology and Paleohydrology. John Wiley and Sons, Chichester, pp. 667–692.

Gaillard, M.-J., Sugita, S., Mazier, F., Trondman, A.-K., Brostro, A., Hickler, T., Kaplan, J.O., Kjellström, E., Kokfelt, U., Kunes, P., Lemmen, C., Miller, P., Olofsson, J., Poska, A., Rundgren, M., Smith, B., Strandberg, G., Fyfe, R., Nielsen, A.B., Alenius, T., Balakauskas, L., Barnekow, L., Birks, H.J.B., Bjune, A., Bjorkman, L., Giesecke, T., Hjelle, K., Kalmina, L., Kangur, M., Vand Der Knaap, W.O., Koff, T., Lageras, P., Latałowa, M., Leydet, M., Lechterbeck, J., Lindbladh, M., Odgaard, B., Peglar, S., Segerstrom, U., Von Stedingk, H., Seppä, H., 2010. Holocene land-cover reconstructions for studies on land cover-climate feedbacks. Clim. Past 6, 483–499.

Goździk, J., 1982. Środowisko przyrodnicze osadnictwa średniowiecznego okolic Rozprzy. Prace i Materiały Muzeum Archeologicznego i Etnograficznego w Łodzi. Ser. Archeol. 29, 138–151.

Grimm, E.C., 1992. TILIA and TILIA GRAPH: pollen spreadsheet and graphics program. In: 8th International Palynological Congress. Program and Abstracts, pp. 1–56 Aix-en-Provence, France.

Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. Paleontological statistics software package for education and data analysis. Palaeontol. Electron. 4 (1), 9. http://palaeo-electronica.org/2001_1/past/issue1_01.htm.

Higham, R., Barker, P., 2004. Timber Castles. University of Exeter Press, Exeter.

Hofmann, G., Werum, M., Lange-Beralot, H., 2011. Diatommen im Süßwasser-Benthos von Mitteleuropa. ARG Gantner Verlag, Koeltz, Königstein.

Juggins, S., 2001. The European Diatom Database. User Guide. http://craticula.ncl.ac.uk, Version 1.0.

Juggins, S., 2007. C2 version 1.5 User Guide. Software for Ecological and Palaeoecological Data Analysis and Visualisation. Newcastle University, Newcastle upon Tyne.

Kabata-Pendias, A., 2010. Trace Elements in Soils and Plants, fourth ed. CRC Press, Taylor & Francis Group, Boca Raton-London-New York.

Kajzer, L., 1993. Zamki i społeczeństwo. Przemiany architektury i budownictwa obronnego w Polsce w X – XVIII wieku. Wydawnictwo Uniwersytetu Łódzkiego, Łódź.

Kajzer, L., 2007. Polska Centralna w XIII wieku – wstępna próba charakterystyki archeologicznej. Archaeol. Hist. Pol. 16, 19–40.

Kamińska, J., 1953. Grody Polski Srodkowej na tle osadnictwa. Łódzkie Towarzystwo Naukowe, Łódź.

Kamińska, J., 1968. Siedlątków, obronna siedziba rycerska z XIV wieku. Prace i Materiały Muzeum Archeologicznego i Etnograficznego w Łodzi. Ser. Archeol. 15, 15–88.

Kenyon, J.R., 1990. Medieval Fortification. Leicester University Press, Leicester.

Kittel, P., Muzolf, B., Płóciennik, M., Elias, S., Brooks, S.J., Lutyńska, M., Pawłowski, D., Stachowicz-Rybka, R., Wacnik, A., Okupny, D., Głąb, Z., Mueller-Bieniek, A., 2014. A multi-proxy reconstruction from Lutomiersk-Koziówki, Central Poland, in the context of early modern hemp and flax processing. J. Archaeol. Sci. 50, 318–337.

Kittel, P., Płóciennik, M., Borówka, R.K., Okupny, D., Pawłowski, D., Peyron, O., Stachowicz-Rybka, R., Obremska, M., Cywa, K., 2016. Early Holocene hydrology and environments of the Ner River (Poland). Quat. Res. 85 (2), 187–203.

Kittel, P., Sikora, J., Wroniecki, P., 2015. The morphology of the Luciąża River valley floor in the vicinity of the Rozprza medieval ring-fort in light of geophysical survey. Bull. Geogr. Phys. Geogr. Ser. 8, 95–106.

Kittel, P., Sikora, J., Wroniecki, P., 2018. A Late Medieval motte-and-bailey settlement in a lowland river valley landscape of central Poland. Geoarchaeology. http://dx.doi.org/10.1002/gea.21676. (in press).

Kłysik, K., 1993. Główne cechy klimatu. In: Pączka, S. (Ed.), Środowisko geograficzne Polski Środkowej. Wydawnictwo Uniwersytetu Łódzkiego, Łódź, pp. 109–134.

Kłysik, K., 2001. Warunki klimatyczne. In: Liszewski, S. (Ed.), Zarys monografii województwa łódzkiego. Funkcja regionalna Łodzi i jej rola w kształtowaniu województwa. Łódzkie Towarzystwo Naukowe, Łódź, pp. 68–81.

Kołaczek, P., Zubek, S., Błaszkowski, J., Mleczko, P., Margielewski, W., 2013. Erosion or plant succession—How to interpret the presence of arbuscular mycorrhizal fungi (Glomeromycota) spores in pollen profiles collected from mires. Rev. Palaeobot. Palynol. 189, 29–37.

Koszałka, J., 2014. Źródła archeobotaniczne do rekonstrukcji uwarunkowań przyrodniczych oraz gospodarczych grodu w Łęczycy. In: Grygiel, R., Jurek, T. (Eds.), Początki Łęczycy, T. I. Archeologia Srodowiskowa Sredniowiecznej Łęczycy. Przyroda – Gospodarka – Społeczeństwo, Łódź, pp. 191–241.

Krammer, K., Lange-Bertalot, H., 2008a. Bacillariophyceae 2, Ephitemiaceae, Bacillariaceae, Surirellaceae. In: Ettl, H., Gerloff, J., Heyning, H., Mollenhauer, D. (Eds.), Süsswasserflora von Mitteleuropa Bd. 02/2, Fisher, Stuttgardt.

Krammer, K., Lange-Bertalot, H., 2008b. Bacillariophyceae 3, Centrales, Fragilariaceae, Eunotiaceae. In: Ettl, H., Gerloff, J., Heyning, H., Mollenhauer, D. (Eds.), Süsswasserflora von Mitteleuropa Bd. 02/3, Fisher, Stuttgardt.

Krammer, K., Lange-Bertalot, H., 2010. Bacillariophyceae 1, Naviculaceae. In: Ettl, H., Gerloff, J., Heyning, H., Mollenhauer, D. (Eds.), Süsswasserflora von Mitteleuropa Bd. 02/1, Fisher, Stuttgardt.

Krammer, K., Lange-Bertalot, H., 2011. Bacillariophyceae 4, Achnanthaceae. In: Ettl, H., Gärtner, G., Gerloff, J., Heyning, H., Mollenhauer, D. (Eds.), Süsswasserflora von

Mitteleuropa Bd. 02/4, Fisher, Stuttgardt.

Krawczyk, A., Krąpiec, M., 1995. Dendrochronologiczna baza danych. In: Materiały II Krajowej Konferencji: Komputerowe wspomaganie badań naukowych. Wrocław, pp. 247–252.

Krąpiec, M., 1998. Oak dendrochronology of the Neoholocene in Poland. Folia Quat. 69, 5–134.

Krąpiec, M., Walanus, A., 2011. Application of the triple photomultiplier liquid spectrometer Hidex 300SL in radiocarbon dating. Radiocarbon 53, 543–550.

Kurnatowski, S., 1963. Uwagi o kształtowaniu się stref zasiedlania dorzecza Obry w czasie od środkowego okresu epoki brązu do późnego średniowiecza. Archeol. Pol. 8 (2), 181–218.

Lange-Bertalot, H., Metzeltin, D., 1996. Indicators of Oligotrophy. 800 taxa representative of three ecologically distinct lake types. In: In: Lange-Bertalot, H. (Ed.), Iconographia Diatomologica: Annotated Diatom Micrographs, vol. 2. Koeltz Scientific Books, Königstein, pp. 1–390.

Latałowa, M., 1998. Botanical analysis of a bundle of flax (*Linum usitatissimum* L.) from an medieval site in northen Poland; a contribution to the history of flax cultivation and its field weeds. Veg. Hist. Archaeobotany 7, 97–107.

Lecointe, C., Coste, M., Prygiel, J., 1993. "OMNIDIA": software for taxonomy, calculation of diatom indices and inventories management. Hydrobiologia 269/270 (1), 509–513.

Line, J.M., Birks, H.J.B., 1996. BSTICK Version 1.0. Unpublished computer program. Botanical Institute, University of Bergen.

Lisitsyna, O., Giesecke, T., Hicks, S., 2011. Exploring pollen percentage threshold values as an indication for the regional presence of major European trees. Rev. Palaeobot. Palynol. 166, 311–324.

Lityńska-Zając, M., 2005. Chwasty w uprawach roślinnych w pradziejach i wczesnym Sredniowieczu. Instytut Archeologii i Etnologii PAN.

Lotter, A.F., Juggins, S., 1991. PLOPROF, TRAN and ZONE. Programs for plotting, editing and zoning of pollen and diatom data. INQUA Commission for the study of Holocene. Work. Group Data Handing Meth. Newslett. 6.

Luoto, T.P., 2011. The relationship between water quality and chironomid distribution in Finland – a new assemblage-based tool for assessments of long-term nutrient dynamics. Ecol. Indic. 1, 255–262.

Marks, L., 2011. Chapter 23-Quaternary glaciations in Poland. In: In: Ehlers, J., Gibbard, P.L., Hughes, P.D. (Eds.), Developments in Quaternary Sciences, vol. 15. pp. 299–303.

Matuszkiewicz, J.M., 2008. Potencjalna roślinność naturalna Polski (Potential Natural Vegetation of Poland). IGiPZ PAN, Warszawa. http://www.igipz.pan.pl/Roslinnosc-potencjalna-zgik.html, Accessed date: 10 March 2017.

Matuszkiewicz, W., 2001. Przewodnik do oznaczania zbiorowisk roślinnych Polski. Wydawnictwo Naukowe PWN, Warszawa.

Moller Pillot, H.K.M., 2009. Chironomidae Larvae. Biology and Ecology of the Chironomini. KNNV Publishing, Zeist.

Moller Pillot, H.K.M., 2013. Chironomidae Larvae of the Netherlands and Adjacent Lowlands, Biology and Ecology of the Aquatic Orthocladiinae, Prodiamesinae, Diamesinae, Buchonomyiinae, Podonominae, Telmatogetoninae. KNNV Publishing, Zeist.

Müller-Wille, M., 1966. Mittelalterliche Burghügel ("Motten") im nördlichen Rheinland. Beih. Bonn. Jahrbücher 16, 1–115.

Mycielska-Dowgiałło, E., Ludwikowska-Kędzia, M., 2011. Alternative interpretations of grain-size data from Quaternary deposits. Geologos 17, 189–203.

Nalepka, D., Walanus, A., 2003. Data processing in pollen analysis. Acta Palaeobot. 43 (1), 125–134.

Nevalainen, L., Sarmaja-Korjonen, K., Luoto, T.P., 2011. Sedimentary Cladocera as indicators of past water-level changes in shallow northern lakes. Quat. Res. 75 (3), 430–437.

Panyshko, S.D., 2014. Sproba rekonstruktsiyi zovnishnʹoho vyhlyadu piznʹoserednʹovichnykh ukriplenʹ "motte and bailey" na Volyni za yikh zovnishnimy morfolohichnymy oznakamy. Visnyk Natsionalʹnoho Universytetu "Lʹvivsʹka Politekhnika" 784, 252–262.

Pawłowski, D., Kloss, M., Obremska, M., Szymanowski, M., Żurek, S., 2012. Evolution of small valley mire in Central Poland as a result of hydroclimatic oscillations. Geochronometria 39, 133–148.

Pawłowski, D., Milecka, K., Kittel, P., Woszczyk, M., Spychalski, W., 2015a. Palaeoecological record of natural changes and human impact in a small river valley in Central Poland. Quat. Int. 370, 12–28.

Pawłowski, D., Kowalewski, G., Milecka, K., Płóciennik, M., Woszczyk, M., Zieliński, T., Okupny, D., Włodarski, W., Forysiak, J., 2015b. A reconstruction of the palaeohydrological conditions of a floodplain: a multi-proxy study from the Grabia River valley mire, central Poland. Boreas 44, 543–562.

Pawłowski, D., Borówka, R.K., Kowalewski, G., Luoto, T.P., Milecka, K., Nevalainen, L., Okupny, D., Płóciennik, M., Woszczyk, M., Zieliński, T., Tomkowiak, J., 2016. The response of flood-plain ecosystems to the Late Glacial and Early Holocene hydrological changes: a case study from a small Central European river valley. Catena 147, 411–428.

Pełechaty, M., Pukacz, M., Apolinarska, K., Pełechata, A., Siepak, M., 2013. The significance of Chara vegetation in the precipitation of lacustrine calcium carbonate. Sedimentology 60, 1017–1035.

Prentice, I.C., 1985. Pollen representation, source area, and basin size: toward a unified theory of pollen analysis. Quat. Res. 23, 76–86.

Ralska-Jasiewiczowa, M., Goslar, T., Różański, K., Wacnik, A., Czernik, J., Chróst, L., 2003. Very fast environmental changes at the Pleistocene/Holocene boundary, recorded in laminated sediments of Lake Gościąż, Poland. Palaeogeogr. Palaeoclimatol. Palaeoecol. 193, 225–247.

Reille, M., 1998. Pollen et Spores d'Europe et d'Afrique du Nord. Supplement 2. Laboratoire de Botanique historique et palynologie, Marselle.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatt, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 Years cal BP. Radiocarbon 55 (4), 1869–1887.

Rinn, F., 2005. TSAP-Win. Time Series Analysis and Presentation for Dendrochronology and Related Applications. User Reference, Heidelberg.

Robinson, C., 1994. Lagon Grande di Monticchio, southern Italy: a long record of environmental change illustrated by sediment geochemistry. Chem. Geol. 118, 235–254.

Rolland, N., Larocque, I., 2007. The efficiency of kerosene flotation for extraction of chironomid head capsules from lake sediments samples. J. Paleolimnol 37, 565–572.

Ruiz, Z., Brown, A.G., Langdon, P.G., 2006. The potential of chironomid (Insecta: Diptera) larvae in archaeological investigations of floodplain and lake settlements. J. Archaeol. Sci. 33, 14–33.

Rydelek, P., 2013. Origin and composition of mineral constituents of fen peats from eastern Poland. J. Plant Nutr. 36, 911–928.

Saether, O., 1979. Chironomid communities as water quality indicators. Holarct. Ecol. 2, 65–74.

Schweingruber, F.H., 1988. Tree Rings - Basics and Applications of Dendrochronology. Kluwer Academic Publishers, Dordrecht.

Schweingruber, F.H., Börner, A., Schulze, E.D., 2011. Atlas of Stem Anatomy in Herbs, Shrubs and Trees, vol. 1 Springer-Verlag Berlin and Heidelberg GmbH & Co. K, Berlin.

Shelley, M., 2013. The Isle of Loch Clunie: the key to the see of Dunkeld. Innes Rev. 64 (1), 39–65.

Shin, D.H., Oh, C.S., Chung, T., Yi, Y.S., Chai, J.Y., Seo, M., 2009. Detection of parasite eggs from a moat encircling the royal palace of Silla, the ancient Korean Kingdom. J. Archaeol. Sci. 36, 2534–2539.

Sikora, J., 2007. Polska Centralna we wczesnym średniowieczu w świetle badań archeologicznych i osadniczych. Slavia Antiq. 48, 121–159.

Sikora, J., Kittel, P., Wroniecki, P., 2015. From a point on the map to a shape in the landscape. Non-invasive verification of medieval ring-forts in Central Poland: Rozprza case study. Archaeol. Pol. 53, 510–514.

Smith, D.N., Howard, A.J., 2004. Identifying changing fluvial conditions in low gradient alluvial archaeological landscapes: can coleoptera provide insights into changing discharge rates and floodplain evolution? J. Archaeol. Sci. 31, 109–120.

Skripkin, V.V., Kovalyukh, N.N., 1998. Recent developments in the procedures used at the SSCER Laboratory for the routine preparation of lithium carbide. Radiocarbon 40 (1), 211–214.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen Spores 13, 615–621.

Sugita, S., 2007. Theory of quantitative reconstruction of vegetation I: pollen from large sites REVEALS regional vegetation composition. Holocene 17, 229–241.

Szeroczyńska, K., Sarmaja-Korjonen, K., 2007. Atlas of subfossil Cladocera from central and Northern Europe. Friends of Lower Vistula Society, Świecie, pp. 1–87.

Szymczyk, A., 2015. Relacje między zespołami szczątków karpologicznych a współczesną roślinnością małych, płytkich zbiorników wodnych. Reprezentacja współczesnej roślinności i rozmieszczenie makroszczątków w osadach wybranych zbiorników Wyżyny Śląskiej. Wydawnictwa Uniwersytetu Śląskiego, Katowice, pp. 173.

ter Braak, C.J.F., Šmilauer, P., 2002. CANOCO Reference Manual and CanoDraw for Windows User's Guide: Software for Canonical Community Ordination. Microcomputer Power, Ithaca, NY, USA Version 4.5.

Thormann, M.N., Currah, R.S., Bayley, S.E., 1999. The mycorrhizal status of the dominant vegetation along a peatland gradient in southern boreal Alberta, Canada. Wetlands 19, 438–450.

Turkowska, K., 1988. Rozwój dolin rzecznych na Wyżynie Łódzkiej w późnym czwartorzędzie. Acta Geogr. Lodz. 57, 1–157.

Vallenduuk, H.J., Moller Pillot, H.K.M., 2007. Chironomidae Larvae of the Netherlands and Adjacent Lowlands. General Ecology and Tanypodinae. KNNV Publishing, Zeist.

Velichkevich, F.Yu., Zastawniak, E., 2006. Atlas of Vascular Plant macroremains from the Pleistocene of central and Eastern Europe, Part II – Herbaceous Dicotyledons. W. Szafer Institute of Botany, Polish Academy of Sciences, Krakow.

Wachecka-Kotkowska, L., 2004. Ewolucja doliny Luciąży – uwarunkowania klimatyczne a lokalne. Acta Geogr. Lodz. 86, 1–161.

Ward, P., Renssen, H., Aerts, J., van Balen, R., Vandenberghe, J., 2008. Strong increases in flood frequency and discharge of the River Meuse over the late Holocene: impacts of long-term anthropogenic land use change and climate variability. Hydrol. Earth Syst. Sci. 12, 159–175.

Wick, L., van Leeuwen, J.F.N., van der Knaap, W.O., Lotter, A.F., 2003. Holocene vegetation development in the catchment of Sagistalsee (1935 m asl), a small lake in the Swiss Alps. J. Paleolimnol. 30, 261–272.

Wiklund, J.A., Bozinovski, N., Hall, R.I., Wolfe, B.B., 2010. Epiphytic diatoms as flood indicators. J. Paleolimnol. 44, 25–42.

Zajączkowski, S.M., 1961. Uwagi nad najdawniejszymi dziejami Rozprzy. Rocz. Łódzki 5, 197–202.

Zeeberg, J., 1998. The European sand belt in eastern Europe - and comparison of Late Glacial dune orientation with GCM simulation results. Boreas 27, 127–139.

Zielski, A., Krąpiec, M., 2004. Dendrochronologia. Wydawnictwo Naukowe PWN, Warszawa.

Zoppi, U., Crye, J., Song, Q., Arjomand, A., 2007. Performance evaluation of the new AMS system at Accium Biosciences. Radiocarbon 49, 173–182.

Chapter V. A closer look into a medieval moat – the temporal and spatial reconstruction of habitat mosaic and ecosystem functioning

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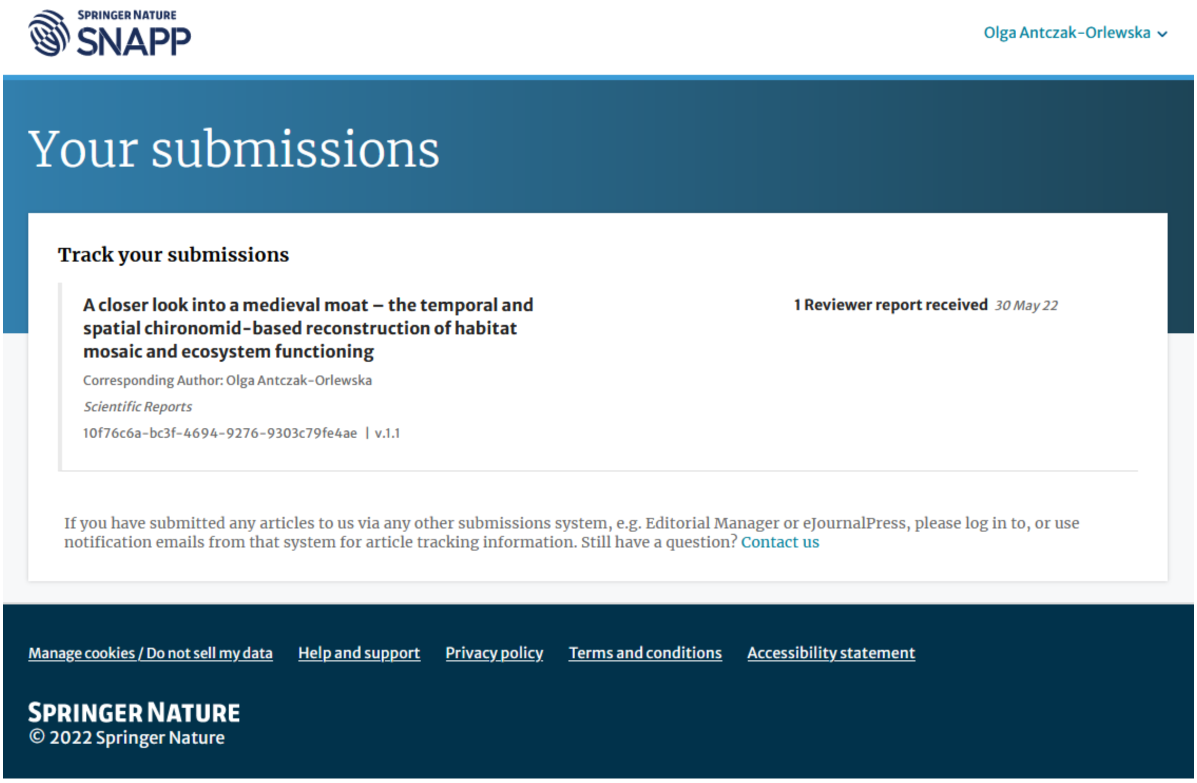

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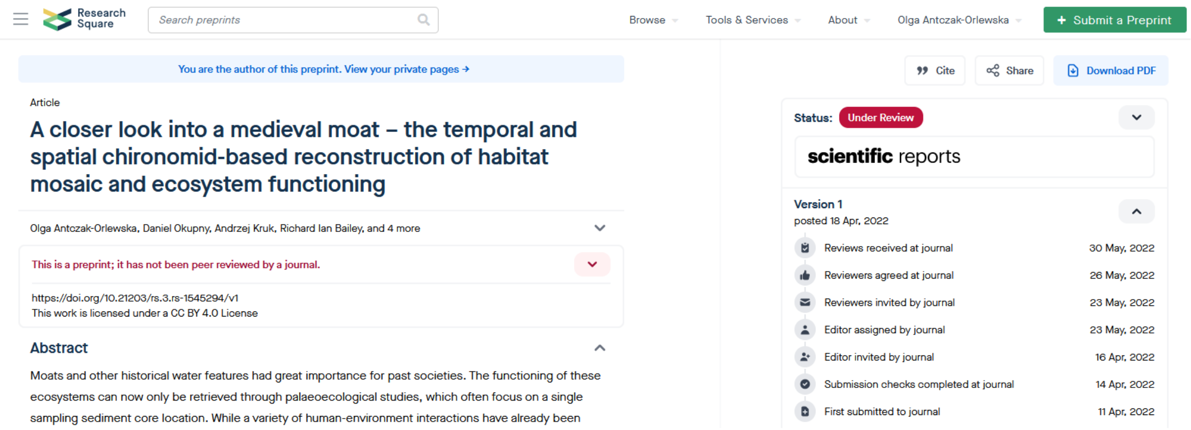

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Abstract

Moats and other historical water features had great importance for past societies. The functioning of these ecosystems can now only be retrieved through palaeoecological studies, which often focus on a single sampling sediment core location. While a variety of human-environment interactions have already been

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A closer look into a medieval moat – the temporal and spatial chironomid-based reconstruction of habitat mosaic and ecosystem functioning

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Abstract

Moats and other historical water features had great importance for past societies. The functioning of these ecosystems can now only be retrieved through palaeoecological studies, which often focus on a single sampling sediment core location. While a variety of human-environment interactions have already been examined, the spatio-temporal habitat changes within a medieval moat are presented here for the first time. Using data from four cores of organic deposits taken from different areas within the moat system, we describe ecological states of the moat based on subfossil Chironomidae assemblages and accompanying sedimentological and geochemical data, using Kohonen's artificial neural network, the canonical correspondence analysis, and generalised linear modelling. We found that chironomid assemblages differed in the spatio-temporal distribution of their habitats, depending mostly on depth differences and fresh water supply from an artificial channel. Paludification and terrestrialisation also did not happen simultaneously across the moat system, being greatly influenced by human activity. The results presented here demonstrate the importance of a multi-aspect approach in environmental archaeology, focusing not only the human environment, but also on the complex ecology of the past ecosystems.

Keywords: palaeoecology, Chironomidae, self-organising map (SOM), Middle Ages, central Poland

Introduction

The diversity of habitats and of the mutual connections between organisms and their environment can now be studied in even the most extreme ecosystems, including historical ecosystems no longer present. Moats were artificial bodies of water providing defence for inhabited strongholds in medieval times. Ecological studies of moats can therefore provide a window into historical influences of human activity on natural ecosystems. Ecological studies can be carried out on moats that have either been preserved from historical times (e.g. [1,2]) or have been recently reconstructed. However, these modern moats do not perform the same function today as in the Middle Ages or Early Modern Period [3], and their aquatic ecosystems may therefore differ. The medieval stronghold's inhabitants influenced water conditions by changing its trophic state, creating new habitats by placing construction elements, modifying its hydromorphology and sedimentation of defined types of water deposits, and their enrichment with selected metals (see [4,5]). Therefore, the only way to get a clear window into those past ecosystems is through palaeoecological studies.

Geochemical studies of historical layers (such as core samples) conducted so far have in many cases confirmed their indicator role in environmental archaeology [6]. The clearly higher Pb and Cu concentrations in the sediments of medieval moats have been used to determine the course of historical watercourses. However, the grain and mineral composition of sediments influences their susceptibility to metal sorption [7]. Therefore, geochemical mapping of archaeological sites, aiming to assess the distribution and characteristics of metallic pollutants in the environment, should take into account the location of the studied cores.

The chosen location of cores also influences paleoecological studies. Typically, paleoecological studies are based on one core of sediment, taken from the deepest (mostly central) part of the (palaeo)lake, on the assumption that the subfossil remains of the organisms once living in different parts of the water body are passively transported over time and deposited into the deepest area of the lake bottom [8]. This way, representative biotic records can be obtained with only one drilling, reducing cost and time of analyses. However, in the case of macrofossils, diatoms, or cladocerans, littoral taxa can be underrepresented in sequences derived from one core [9-11]. Analogously, chironomid head capsules accumulate mostly near the habitat of the larvae, and offshore transport is primarily observed in the less well preserved early instars [12], which may produce some biases. Generally, if the subfossil record is expected to adequately represent the environment of sedimentation and track particular events, multiple coring within the (palaeo)lake or mire is needed [8,13].

In environmental archaeology, it is recommended to take at least two cores for palaeoecological analyses – one from the studied site (on-site profile) and one from an area separated from direct human activity (off-site) (e.g. [14,15]). This allows examination of both local and regional vegetation history, and also of environmental information, such as past water level or temperature changes. Due to differences in deposition between aquatic and terrestrial systems, “wet sites” or “wet features” (such as a moat) allow examination with use of a wider range of ecological proxy analyses, based on organic deposits within cores sampled directly from archaeological trenches.

Our on-site palaeoecological investigations were an integral part of archaeological study of a stronghold’s moat system in Rozprza (central Poland; see ‘Study system’ section, below) [5,16]. The main sediment core from the studied moat has already been investigated in detail (see [5]). The results indicated that when the stronghold was inhabited (14th-15th century AD), the moat was infilled with shallow water with possible episodes of rinsing through an artificial channel from the nearby river. Changes in water trophic state were tracked using chironomid-based models, and the Chironomidae-inferred summer temperatures of the Late Vistulian came from the nearby palaeomeander [17]. The Holocene chironomid sequence in the palaeomeander core was too low in abundance for quantitative reconstructions. However, even profiles with a depauperate biotic record can be used to obtain some ecological information, especially if treated simultaneously with other analyses. Therefore, we took additional cores from potentially different habitats (cf. [18]) within the moat, in order to obtain a more complete picture of environmental changes and human impact on the ecosystem in both time and space.

Though chironomids have proven to be useful in environmental archaeology (e.g. [19-23]), they have not previously been used for spatial reconstructions of artificial features. Moats, barays and other anthropogenic ponds have more limited potential to accumulate most of the subfossil remains in one point than lakes, mostly because of the specific basin morphology. Therefore, a carefully constructed spatial approach is required, taking into consideration habitat mosaics within the moat ecosystem. Chironomidae larvae represent an ideal proxy for spatial reconstruction of artificial features. They are ecologically diverse, sensitive to environmental changes, and indicative of particular ecosystem conditions and processes [24,25]. Therefore, their distribution in shallow reservoirs with complex morphometry may be diversified and earlier studies based on one sediment profile [5] need to be complemented in order to cover the spatial aspect.

Considering these issues, our main goal was to reconstruct changes in habitat distribution across the stronghold's moat system over time. We aimed to examine: 1) whether the Chironomidae communities were consistent in different parts of the moat, and 2) if they changed simultaneously and/or evenly throughout the moat basin. We hypothesised that even in such a small and shallow water body as a moat, the differences between cores would be significant and, thus, the habitat mosaic and more aspects of stronghold functioning could be reconstructed.

Study site

Rozprza is located in central Poland, about 60 km south of Łódź in the Piotrków Plain [26]. The study site is situated in the middle reach of the Luciąża River valley, a tributary of the Pilica River in the Vistula River basin (Fig. 1).

Nowadays, the late medieval stronghold remnants with their moat system are situated in an area covered by fields and meadows between the Rozprza and Łochyńsko villages (51˚18'07'' N; 19˚40'04'' E). The poorly preserved traces of moats, ramparts and baileys are however still visible in the field (Fig. 1C) and on DEMs (Digital Elevation Models). The study site is located on the valley floor with regulated channels of the Luciąża, Rajska and Bogdanówka rivers, as well as a dense network of drainage canals (Fig. 1B).

The studied fortress was established on the Plenivistulian fluvial terrace remnant, in the area of the widely spread valley floor. Such a location of the motte-and-bailey was reasonable for defensive reasons, as the sandy terrace remnant was protected by the surrounding swampy areas within the valley floor [16,27]. However, the hillock of the terrace remnant occupied by the motte in the late Middle Ages was very low (up to 1 m).

Late medieval motte-and-bailey timber castle at Rozprza was built about 1330 AD and replaced an earlier timber and earth ringfort of unclear chronology (between 11th and 13th century AD). Motte-and-bailey castles were common in western Europe already in the 11th century [28] but introduced to Poland much later, in the 13th century [29]. In the 14th and 15th centuries AD it was one of the most popular types of rural noble residences.

The main moat of the Rozprza motte-and-bailey was established ca. 1330 AD and was later filled with organic (gyttja and peat) and partially inorganic deposits containing rich remains of wood (Fig. 2). The fill of the main moat was the subject of a detailed palaeoenvironmental study by Kittel et al. [5]. The accumulation of overbank silty sandy organic mud took place within the moat ditch system as late as in the 18th or 19th c. AD [5,16]. The main moat had a width of 17–21 metres and a trapezoidal cross-section with a depth of 0.5 m, up to ca. 1.3 m. Wooden constructions were recorded near the inner slope of the moat ditch – in the form of a palisade created by two rows of vertical, sharpened wooden poles, and horizontal beams lying behind them. Those constructions were covered with thick layers of slope deposits (sand with organic mud). Many large chunks of wood (branches and boughs) were recorded in peat and organic mud of the upper unit of the moat fill close to the inner slope of the main moat [16].

The second moat had a width of about 11 m and a depth of ca. 0.5 m. In the trapezoid cross-section it has a flat bottom. The fill of the moat consisted of sand with organic admixtures at the very bottom, peat with silts, sands and organic mud, and also slope wash deposits on the moat slopes. The chronology of the feature formation has been estimated to 1485–1634 AD based on ^{14}C data (Table 1). It demonstrates that the secondary moat was built probably in the early 16th century AD. However, the analysis of most archaeological small finds obtained during field works, mostly pottery fragments, estimated their age to the period between 14th and a mid-15th century AD. Evidence of human activity on the stronghold in the 16th century AD is also very limited. Therefore, an establishment of the second moat in the 15th century AD cannot be excluded (see [16]).

Results and interpretation

Chronology of moat deposit accumulation

In total six radiocarbon dates were used for the construction of the age-depth model for the RP W3(2) core from the deepest studied part of the main moat (Table 1, Supplementary Table S1) [5,16]. Based on dendrochronological data from a wooden fragment from the moat's bottom, establishment of the main moat was defined to ca. 1330 AD. In the early phase, the moat was filled with gyttja. In the 1st half of 16th century AD, a sedentation of peat began. In the early 18th c. AD the peat was covered with overbank alluvia (Fig. 2).

A comparable pattern of evolution of the main moat was reconstructed based on the age-depth model for the RP W3(4) core (Table 1, Supplementary Table S2). The lacustrine deposition was replaced by peat sedentation in the mid-15th c. AD. The accumulation of overbank alluvia may have been initiated in the first decades of the 18th c. AD. The fill of the western part of the moat was covered in 1944 AD by an embankment from the destroyed stronghold mound [5].

The chronology of the main moat fills in the RP W1 core confirms an establishment of this moat in the 1st half of the 14th c. AD. Moreover, the eastern part of the wet defensive system was filled with peat from its beginning up to 16th c. AD (Table 1, Supplementary Table S3). The upper part of the moat fill in the RP W1 area was probably removed during melioration works in 20th c. AD.

The absolute chronology of the fill of the secondary moat, studied in the RP F2 core, demonstrates that this additional defensive ditch has been established most probably in the 1st half of 16th c. or possibly in the late 15th c. AD (Table 1, Supplementary Table S4). From 18th c. AD, an effect of flooding is visible recorded by sandy admixtures in organic deposits of the moat fill (cf. [16]).

Self-organising map and Chironomidae Indicator Species Analysis

The self-organising map (SOM) allowed clusters of core samples with similar community composition to be produced. The taxa significantly associated with them were then identified with the Indicator Species Analysis.

Two main clusters were distinguished in the output layer of the SOM: X and Y, comprising the respective pairs of subclusters: X1 and X2, and Y1 and Y2 (Fig. 3). The subclusters were ordered according to the gradient observed in the number of indicator species (Fig. 4). Subcluster X1 represents unfavourable conditions for Chironomidae development, mostly overbank deposits (see Fig. 2). It contains surface samples from RP W3 cores (from 51 cm depth in W3(2) and from 55 cm in the W3(4) profile), samples from 91 to 87 cm of W3(2) core depth, 85-83 cm and 73 cm of W3(4) core depth, most samples from RP W1 core, and the whole sequence of the second moat (RP F2 core). The samples from 83 to 55 cm of RP W3(2) core, 75 cm and 63-57 cm of RP W3(4) core, as well as one sample (29 cm depth) from RP W1 core were assigned to subcluster X2. They were associated with high organic matter (OM) content (mean 59.9%) and slightly acidic (mean pH = 6.6), probably telmatic (marshy) conditions (Fig. 2). Cluster Y represents limnetic conditions. Subcluster Y2 reflects habitat with higher detrital (K, Mg, Ca) and sulphide (Cu, Fe) element concentrations, grouping bottom samples from the RP W3(2) core up to 95 cm and samples of 39-37 cm depth from the RP W1 core (Fig. 3). Samples grouped in the subcluster Y1 (81-77 cm and 71-65 cm core RP W3(4) depth, sample from 21 cm core RP W1 depth) are associated with lower sulphide element content (Fig. 3).

A total of 55 (57%) dipteran taxa were significantly associated with a certain subcluster, i.e. they were indicators of its respective environmental conditions (Fig. 4). Among these, 24 exhibited IndVals significant at $p \leq 0.001$, 20 at $p \leq 0.01$, and 11 at $p \leq 0.05$. An upward trend was observed in the number of such taxa for subclusters in the order X1, X2, Y1, Y2. No palaeoindicator was significantly associated with subcluster X1, eight taxa were significantly associated with X2, 19 with Y1 and 28 with Y2. Therefore, this order of subclusters corresponds to increasingly favourable conditions for development of a rich biota.

The most indicative (at $p<0.001$) morphotypes for subcluster X2 were *Limnophyes-Paralimnophyes* and *Parametriocnemus-Paraphaenocladius*, which are associated with the semi terrestrial habitats with slightly acidic water [30]. Ceratopogonid species grouped as *Dasyhelea*-type seem to have similar preferences [31], while Chironomini taxa linked to X2 prefer shallow, muddy water bodies and can occur in seasonal surface water. Chironomids associated with Y1 were mostly typical of warm, productive, littoral habitats, and many of them are phytophilous (e.g. *Glyptotendipes pallens*-type, *Lauterborniella*). However, also associated with this subcluster were *Tanytarsus lugens*-type and *Paratanytarsus austriacus*-type, often recorded in cold, oligotrophic conditions. Morphotypes significant to subcluster Y2 included both taxa associated with warm, eutrophic stagnant water (e.g. *Micropsectra pallidula*-type, *Cladotanytarsus mancus*-type, *Cryptochironomus*) and those preferring meso- and oligotrophic conditions (e.g. *Psectrocladius barbatipes*-type and *Bezzia*-type). Many of them, such as *Zavreliella* and *Polypedilum sordens*-type are associated with macrophytes. Moreover, several chironomids associated with running water (such as *Nanocladius rectinervis*-type, *Corynoneura coronata*-type and *Parachironomus varus*-type) were recorded with a significant IndVal in this subcluster. This differentiation is confirmed by the results of the chemical composition filling from the upper part of the RP W3(2) core (Fig. 2), because the rich organic sediments (OM even above 90%) are covered by acidic deposits with organic matter content below 7% and very variable concentration of lithophilic elements (for example K range 0.17-2 mg/g). The changes in time of sorption capacity were probably caused by changes in the porosity of the sediments that accumulated in the moat. This feature is the result of the difference between natural and dry bulk density and it is particularly modified by the content of very fine fraction in the sediments [32]. In turn, the increased abundance in nutrients results from a high proportion of the clay fraction, which in the sediments from RP W3(2) often exceeds 3%, with the maximum of 6.45% (Fig. 2). These features of the biogenic accumulation environment influenced conditions for the development of vegetation and chironomids.

Canonical Correspondence Analysis (CCA)

The CCA was done to detect Chironomidae-geochemical signal correlations. Axis 1 explained 11.3% and Axis 2 explained 4.2% of species data variance among individual core samples. For the species-environment relationship variance, 42.1% was explained by Ax1 and 16.0% by Ax2. The analysis (Fig. 5) demonstrated that pH, Ca, Pb, Fe and organic matter ($p<0.01$), as well as Cu and K

($p<0.05$) were significant in shaping Chironomidae assemblages in the moat, with 6.4% of the variance explained by pH, 4.6% by Ca, 4.2% by Pb, and 3.0% by Fe. Organic matter (OM) and Cu both explained 2.3%, while K explained 1.5% of the total variance. Pb was positively correlated and pH negatively correlated with Ax1. The rest of the variables were positively correlated with Ax2.

The samples grouped in the X1 subcluster generally represented conditions unfavourable for aquatic biota. Many of them were characterised by relatively high Pb, probably reflecting increased denudation processes after stronghold abandonment and increased flooding activity in the 18th–19th centuries AD (cf. [5]). This series describes monofraction of the mineral admixture (share of the sand mainly ranges between 70-90% and M_z for 70% number of samples is 1.6-2.2 *phi;* Fig. 2). According to Kittel et al. [21], in the absence of a clear boundary between individual layers, identification of flood activity should include changes of colour sediments, caused by admixture of decomposed and diffused organic matter. In our case, organic matter values varied little among X1 subcluster samples (mean for this section 29.3%) and corresponded with light-grey horizon (overbank organic mud and overbank sandy organic mud *vide*: [5]; Fig. 2) a dozen cm thick. The taxa typical of the telmatic phase of the moat (X2) were associated with low pH. Moreover, *Limnophyes-Paralimnophyes, Parametriocnemus-Paraphaenocladius* and *Polypedilum sordens*-type prefer habitats with high organic matter and iron compounds content. However, among samples classified to the X2 cluster, those from RP W3(2) core were more related to acidic conditions than those from RP W3(4). Generally more alkaline conditions are preferred by the chironomids indicative of the limnetic stage of the moat, in particular to subcluster Y2 (Fig. 5). This is confirmed by the high concentrations of Ca (often above 60 mg/g) (Fig. 2), which is rarely documented in the deposition environment of the hypergenic zone in Central Europe (cf. [33]). Thus, intensive chemical denudation and leaching of mineral substrate of variable origins were confirmed in the catchment of Luciąża River valley, the surface geology and mineralogy of which was documented in detail by Wachecka-Kotkowska [34]. Those taxa (e.g. *Zavreliella* and *Cricotopus bicinctus*-type) prefer habitats with high Ca and K values. Several phytophilous taxa (such as *Paratanytarsus penicillatus*-type, *Corynoneura coronata*-type and *C. arctica*-type) seemed to be more associated with sulphide elements (Cu, Zn), than with pH level. Alkaline conditions are also important to several taxa indicative of the Y1 subcluster (like *Tanytarsus pallidicornis*-type 2), but unlike Y2, these taxa are associated with low element levels (Fig. 5).

In most studied profiles the concentration of sulphide elements was low (Cu: 3.49–57.2 µg/g; Zn: 3.12–210 µg/g; Fe: 1.2–99.3 mg/g) (Fig. 2), but irrespective of lithology, these results are typical for a river valley environment in Central Europe [35]. The stratigraphy differentiation in deposit chemistry indicated that enrichment of Cu and Fe took place during the changes of sedimentation type from organic rich to mineral input or increased humification. Precipitation of colloidal forms of these elements was dependent on changes in the local groundwater level [36]. In the Luciąża River valley the water budget was represented by water flowing underground into the alluvia coming from the post-glacial areas surrounding the Rozprza stronghold (e.g. Radomsko and Dobryszyce Hills), the water of the Luciąża river system, and precipitation water that did not participate in the evapotranspiration processes.

Generalised linear mixed model (GLMM)

To examine whether an individual core can be considered representative of the whole site, we tested for differences in relative chironomid taxon abundances among cores, controlling for sample volume and sample age effects. Diagnostics revealed no significant deviations from model assumptions for the fitted poisson family GLMM. Fixed effect model selection based on AICc revealed the full model to be the best-fitting model, including an interaction between core and species (LL=-3727.7, d.f.=294, AICc=8079.1, weight=1). This indicated a significant difference among cores RP W1, RP W3(2) and RP W3(4) in chironomid relative species abundance distributions. Therefore, there may be some error associated with extrapolating results from a single core across a whole site. The species with the biggest differences among cores in relative abundance were *Chironomus plumosus*-type and *Dicrotendipes notatus*-type, which both are common, often with high share in the samples. However, they had much higher relative abundance in core RP W3(2) than RP W1 (Supplementary Table S5).

Discussion and conclusions

The results based on chironomid assemblages generally confirm three main stages of the moat history: limnetic, telmatic and terrestrial. In addition to the previous study [5], however, we reveal variation in moat habitat overall and in temporal habitat changes across the moat system.

The afore-mentioned three stages of the moat are visible only in its deepest, south-western part (both RP W3 cores) (Fig. 2). Here the ecological processes, such as paludification, lasted longer and the habitat changes were less dynamic, resulting in more stable conditions for biota. However, the limnetic phase was of a different nature in the RP W3(2) and RP W3(4) cores, which were located close (12.5 m) to each other. While fresh water from the artificial canal (see Fig. 1C, 6, [5]) firstly supplied the southern part of the moat, the inflow may have been higher in RP W3(2) than in RP W3(4), probably because of its greater depth (Fig. 6). The significant presence of rheophilic taxa in the former core (indicative for cluster Y2) supports this. Moreover, the sediment chemistry record (Fig. 2), in particular values of Fe/Mn ratio (mostly below 50, average 34.1 for Y2 in RP W3(2) core), suggest higher oxygenation in this part of the moat, which may indicate the course of the water current. A crucial factor in this case could also be the structure of the moat bottom closely related to the groundwater level, which determines the habitat diversification of the plant cover. These processes could lead to the aggregation of soils grains/sediment into concretions and lumps, which when combined with Fe and decomposed organic matter, can lead to development of dense hardly permeable zones [37,38]. Such a situation in the studied area would have a direct impact on the disturbance of vertical water movement and the possibility of plant rooting, determining the specific geochemical cycle between moats-plants-sediments. While habitats in both RP W3 cores during the limnetic phase, with high pH and dense vegetation, could support well-functioning biotic communities, conditions in the shallower part of RP W3(4) were slightly less favourable for chironomids. There, the limnetic stage is reflected mainly in the Y1 subcluster, interrupted by single samples indicating lower diversity of chironomid assemblages. The telmatic phase in this core could have started earlier than in RP W3(2), as indicated by peat deposits and the X2 cluster. This effect may be caused by the location of RP W3(4) close to the moat edge, resulting in faster sedentation and shallowing of the moat bottom.

The north-eastern part of the main moat had worse conditions for chironomid development, as is shown by cluster X1 containing most samples from the RP W1 core (Fig. 2). Generally, the RP W1 core is characterised by relatively uniform lithology, consisting mostly of peat (with periodical supply of the mineral fraction, including sands). It is the result of much shallower conditions of this part of the main moat resulting in dominating sedentation of peat. During the first phase of the moat history (up to ca. 1440 AD), episodes of more complex chironomid assemblages were recorded, as reflected by clusters Y2, X2 and Y1 (Fig. 2), and higher chironomid richness and abundance (Supplementary Fig. S3). They may indicate some limnetic episodes also in the NE part of the moat (Fig. 6), though not as clear and stable as in its deeper southern part. Despite slight differences in the concentration of most elements, they are confirmed by selected geochemical indicators (e.g. increase of Fe/Mn ratio to 82). These episodes are also accompanied by a clear decrease in the values of denudation indicators (i.e. Na/K from 0.12 to 0.04 and Ca/Mg from 0.03 to 0.01) (Fig. 2). The record of the RP W1 core ends approx. 1560 AD, probably because of the anthropogenic removal of the top parts of the moat filling during drainage works in the 20th c. AD.

The second moat (RP F2 core) was created not earlier than in the 2nd half of 15th century, and most probably ca. 1500 AD (see Fig. 2, Supplementary Table S4). In fact, it is not certain whether it was built as a functional moat, or possibly as a dry ditch (e.g. for melioration or defensive purposes). The chironomid scarcity and high admixture of sands (Fig. 2, 5) rather support the later possibility. Moreover, the secondary moat was much narrower (ca. 11 m) than the main one, so active slope processes provided a constant supply of mineral matter (mostly sands). This moat was functioning briefly, as the motte could be redeveloped, probably temporarily in the 16th century AD [5].

The results of habitat reconstruction confirm the modelling (GLMM) outcome that one core does not show the entire history of the moat. This is because a moat is not a typical water body – not only very small and shallow, but also with a specific shape. The steep, almost vertical banks, artificial channels, depth differences and many other features had a crucial impact on the sediment spatial composition and, hence, also on moat functioning. Anthropogenic wood and other artefacts and ecofacts in the bottom can serve as an additional habitat, e.g. for periphyton development.

Besides Rozprza, only a few moats in Europe had hitherto been studied using palaeoecological analyses (e.g. [39-41]), and they mostly focused on human economy and functioning, rarely touching the issue of the moat ecology itself. Moreover, some of these studied defensive objects were dry (e.g. in Prague [42] and Gdańsk [43]). The external moat of the Czermno stronghold [44] seems to be comparable with the Rozprza site, though they cover different time spans. Both features evidenced relatively fast peat sedentation and paludification in comparison with natural water bodies (cf. [17]). Well studied was the moat system in the Tum (Łęczyca) stronghold, including palynological and plant macrofossil analyses from its different parts [45,46]. However, any further spatial reconstruction of the environmental conditions within the feature is provided.

Moats and similar human-made features are hardly comparable with natural ecosystems. While the multiple coring approach is sometimes undertaken i.e. to track past water-level changes [47,48], in such archaeological sites as Rozprza motte, various factors need to be considered, in particular human impact. In waterlogged sites, such as the Serteya Neolithic pile-dwelling, the human-environment relation can be tracked alongside the quantitatively reconstructed climatic background [22,49]. Palaeoecological methods are of great importance while tracking the history of the cities, like Gdańsk [50] and London [51] with the use of profiles of wet sediments.

In the majority of archaeological sites, if palaeoecological studies are undertaken, they focus on the surroundings of the excavations, mainly because of the lack of wet organic sediments to take core from (e.g. [52,53]). Another issue is the cost and time, which need to be taken into consideration with any additional core. In our case, the cores of sediments were taken as monoliths directly from the walls of archaeological trenches, and the profiles were relatively short, which was a great convenience. The additional cores, however, were examined only with respect to lithological and geochemical composition, accompanied by chironomid analysis. With the use of macrofossil analysis, habitat diversity could be even more accurately mapped, which is worth considering in future research.

To sum up, multiple cores are required to get a complete picture of the spatio-temporal changes within the ecosystem. The environmental reconstructions from the deepest part of the moat (RP W3(2)) presented in Kittel et al. [5] are substantiated here, and the results are largely consistent with the core taken from the same trench (RP W3(4)). However, the sequences from the second moat (RP F2) and the NE part of the main moat (RP W1) significantly complement the reconstruction and help give a better understanding of the functioning of moat ecosystems and motte-and-bailey strongholds.

This study represents the first reconstruction of moat habitats during its functioning that consider spatial variation. It is likely that many similar water bodies could be investigated this way, broadening our knowledge about past societies and ecology of such human-made ecosystems.

Material and methods

Fieldwork

The research in Rozprza began with a non-destructive survey carried out in 2013-2015. Methods included analytical field walking, aerial photography, geophysical and geochemical prospecting, as well as thorough geological mapping. A dense network of cores taken with a hand auger resulted in elaboration of detailed cross-sections of the ringfort vicinity. Thanks to this investigation it was possible to localise some archaeological and palaeogeographical features [27,54]. This led to the next extensive, interdisciplinary investigation. This fieldwork was conducted in 2015-2016, with the use of archaeological trenches, geological outcrops and a wide range of palaeoecological studies. They aimed to reconstruct the environmental conditions and settlement history of the mediaeval stronghold at Rozprza [5,16,55].

The procedure of exposing trenches included removing successive 10-cm layers of sediments, distinguishing stratigraphic units within them, and wet-sifting with a 4×4 mm sieve in order to collect archaeological artefacts and ecofacts. All trench walls and collected features were thoroughly documented as orthophotos. The sediments for palaeoecological analyses were collected from the trench walls as monoliths using metal boxes with dimensions of 50×10×10 cm. Thanks to this method, the undisturbed structure of the sediments was preserved.

The RP W1 profile was collected from the deepest section of the trench 1/2015. This trench, with dimensions 2.5×12 m, was exposed in the eastern part of the main moat (Fig. 1C). Wooden vertical posts, associated with numerous fragments of wood, were revealed in the bottom of the moat. The moat was shallow here, reaching up to 50 cm depth. Two cores of sediments were collected from the trench 3/2015 (1.5×25 m), situated in the south-western part of the main moat. The RP W3(2) profile was taken from the deepest part of the main moat and RP W3(4) from its shallower part. Trench 3/2015 exposed the very well preserved moat fill, adjoining the outer rampart and the motte mound, allowing for their full cross-section. The RP F2 profile was taken from the thoroughly deepened and purified wall of the drainage ditch, which currently crosses the secondary moat. The deposits were collected from the deepest part of the smaller southern moat (Fig. 1C).

Digital reconstruction of the main moat relief

The 3D reconstruction model of the bottom of the main moat was prepared within the GIS environment (Qgis, SAGA GIS and PlanlaufTerrain softwares) using point cloud of Airborne Laser Scanning (ALS) already accessible via the Geoportal.gov.pl web service. This was supplemented with results of detailed coring (80 drillings in the distance 1 or 2 m) of the moat as well as results of excavation of archaeological trenches 1/2015 and 3/2015. Contemporary bare earth points covering the moat in the ALS derived point cloud were replaced by points with the height values of the surface of mineral bedrock indicating the original bottom of the moat. Subsequently, all the points were interpolated to obtain a Digital Elevation Model of the stronghold area with the main moat virtually reconstructed and emptied. This allowed for modelling water circulation and subsequent changes of moat states.

Geochemical and sedimentological analysis

Detailed geochemical tests covered material from the four cores presented here (133 samples from 4 cores) (Fig. 2). The basic physical and chemical parameters were the following: organic matter content (LOI – loss on ignition), calcium carbonate ($CaCO_3$) content (volumetric measurement of CO_2 from conversion of $CaCO_3$ by 10% HCl) and reaction (pH in distilled water). All parameters were measured in 2-cm resolution according to the procedure by Tolksdorf et al. [56]. Ash material without organic matter (remaining after LOI) was dissolved with concentrated 65% HNO_3, 10% HCl and H_2O_2 in a Berghof Speedwave microwave mineralizer. Elements with palaeoenvironmental significance (Na, K, Ca, Mg, Fe, Mn, Cu, Zn and Pb) identified in the resulting solution were marked by the atomic absorption spectroscopy (AAS) method with used of Solar Unicam and following procedure after Borówka [36].

Paleoenvironmental conditions responsible for the sedimentation of the studied deposits were interpreted by determining the quantitative ratios of the elements (such as: Na/K, Fe/Mn and

Cu/Zn) with the assumption that the individual lithogeochemical components came from different sources (cf. [49]).

The grain size composition of mineral ash (treated as terrigenous silica) remaining after solution was prepared as in Clift et al. [57] as determined using a Mastersizer 3000 laser particle-size analyser (Malvern). The grain-size data were stored and processed using GRADISTAT software v. 8.0 [58].

Chironomidae analysis

The samples for Chironomidae analysis were taken as contiguous 2-cm slices of the sediment from each profile, besides RP W3(2) core, from which they were collected with 4 cm resolution. The number of samples analysed in each profile was similar (ranging between 23 in RP W1 and 27 in RP W3(2)), while sample volume varied between 5 cm^3 and 70 cm^3.

Chironomidae preparation methods followed Brooks et al. [25]. The sediments were passed through a 63 µm mesh sieve. If head capsule (hc) concentration in the sediments was low, kerosene flotation was used following the procedure of Rolland and Larocque [59]. Processed sediment was scanned under a stereo-binocular microscope. Where applicable, a minimum of 50 (preferably 100) chironomid head capsules from each sample were picked and mounted in Euparal®. Identification of taxa followed Schmid [60], Brooks et al. [25], and Andersen et al. [61]. Ecological preferences of identified taxa are based mainly on Brooks et al. [25], Vallenduuk and Moller Pillot [62], Moller Pillot [30,63], and Luoto [31]. The chironomid sequences are presented on stratigraphic diagrams (Supplementary Figures S1-S4) created with C2 software [64].

Radiocarbon and dendrochronological dating

The chronology of the Rozprza moat system was estimated using radiocarbon (^{14}C) and dendrochronological methods. Both dendrochronological and conventional radiocarbon dating of organic material using the LSC technique were performed in the Laboratory of Absolute Dating in Kraków (Poland). A few wood fragments sampled during moat system exploration [16] were dendrochronologically dated using standard procedures [65].

A total of 15 samples from moats of the Rozprza motte-and-bailey were collected for radiocarbon (^{14}C) dating (Table 1). Thirteen of these were sampled from three cores of the main moat and two were from the southern secondary moat (cf. [16]). For the full cross-section of the deepest part of the main moat, seven dates were obtained for the RP W3(2) core and four for RP W3(4) [5]. Two more datings were made for the RP W1 core from the eastern shallow part of the main moat, and a further two ^{14}C dates for the RP F2 core in the southern additional moat.

Twelve samples of bulk organic deposits (organic mud, peat or gyttja) were dated using the liquid scintillation technique (LST) and three samples of selected terrestrial plant macrofossils dated using the accelerator mass spectrometry technique (AMS). All samples were chemically pre-treated using the AAA (acid-alkali-acid) method. The procedure for conventional radiocarbon dating of organic material using the liquid scintillation counting method (LSC) included the standard synthesis of benzene from organic samples [66]. ^{14}C measurements were carried out with a 3-photomultiplier spectrometer, the HIDEX 300SL [67] and Quantulus 1220. Organic samples dated using the AMS technique were combusted, purified, and graphitised with Fe catalyst [68,69]. The mixture of graphite and Fe powder was pressed into a target holder and measured with the AMS system at the Centre for Applied Isotope Studies at the University of Georgia, USA [70] or in the Accelerator Mass Spectrometry Laboratory (D-AMS laboratory code) in Seattle (see [71] for details).

Calibrated radiocarbon ages (BC/AD) were made using the IntCal20 radiocarbon calibration dataset [72] and the OxCal 4.4.2 calibration software [73,74]. The age-depth curves for studied cores were elaborated based on the OxCal P_Sequence model [75]. The age-depth models were obtained separately for four studied cores. More detailed chronology was obtained for the longest RP W3(2) core and the new model slightly differs from that published by Kittel et al. [5]. For the RP W3(2) core and the RP W3(4) core, dendrochronological dates for a fragment of wooden ecofact found in the very bottom of the main moat was included into both age-depth models (cf. [5]). More detailed chronology has been obtained for the longest RP W3(2) profile and the new model slightly differs from that published by Kittel et al. [5]. A dendrochronological date from a fragment of wooden ecofact found in the very bottom of the main moat was included into RP W3(2) and RP W3(4) age-depth models (cf. [5]). For an estimation of absolute chronology of selected palaeoenvironmental events, the probability distributions of the modelled calendar ages for 1-cm intervals of deposits were calculated (Supplementary Tables S1-S4). It was used for estimation of absolute chronology of selected palaeoenvironmental events.

Statistical data analyses

Self-organising map and Indicator Species Analysis

Patterns in the dipteran assemblages were recognized with Kohonen's (unsupervised) artificial neural network (ANN), also referred to as a self-organising map (SOM) [76,77]. Artificial neural networks (ANNs) are simple structural and functional models of the brain. ANNs have many advantages, which allow a researcher to apply them to "difficult" data. They do not require any *a* *priori* specification of the model underlying a studied phenomenon because they learn it based on the processed data. They are also robust to noise in data [78,79]. This is important for the purposes of the present study, because taxa abundances in field samples do not reflect exactly the original abundances of populations [80]. Additionally, in palaeoecological research the long time separating the living populations and their sampling, and resulting decomposition and fragmentation additionally enhance the problem [81]. ANNs are also robust to non-linear relationships between variables and to non-normal distributions in data [82,83]. This is also crucial in this study because the counts of rare species cannot be effectively normalised by any transformation due to their absence in most samples and therefore strongly skewed variable distributions [82,84]. Furthermore, dipteran assemblages are shaped by many abiotic and biotic factors that are related in complex ways.

Kohonen's ANNs are constructed from data processing units (neurons) arranged in two layers: an input layer used for data input, and an output layer responsible for data structuring and output. The data used for the SOM analysis comprised log-transformed abundances of 97 taxa recorded in 79 non-empty core samples.

They were displayed on the input layer comprising 97 neurons (one input neuron per taxon). The output neurons were arranged as a two-dimensional rectangular lattice. The number of output neurons should be close to $5\sqrt{n}$, where n is the number of samples; in this case the result was 44 (see [85]). Therefore, the final size of the lattice was 7 × 6 (= 42) neurons.

Each input neuron repeatedly transmitted signals to each output neuron. These signals were strengthened or weakened by modifying the weight of the connections between neurons. On this basis, a virtual dipteran core sample (DCS) was created in each output neuron.

The distance between virtual DCSs on the two-dimensional lattice exhibited their mutual dissimilarity, i.e. virtual DCSs in distant output neurons differed considerably while those in neighbouring output neurons were similar. The latter might not be true when the neighbouring output neurons were in different (sub)clusters as the virtual DCSs, and respective output neurons, were additionally clustered with hierarchical cluster analysis (with Ward algorithm and Euclidean distance) [78,85,86].

Finally, each real DCS was assigned to the best matching virtual DCS and the respective output neuron. Therefore, the mutual distance of the real DCSs on the two-dimensional lattice was a derivative of the mutual dissimilarity and position of virtual DCSs: significantly dissimilar real DCSs were located in distant neurons, while similar real DCSs were located in the same neuron or in adjoining neurons [83].

The batch training algorithm was chosen for the purpose of network training, because it does not require any training rate factor to be specified [78]. The network training and the clustering of virtual DCSs were performed with the use of the SOM Toolbox [87] developed by the Laboratory of Information and Computer Science at the Helsinki University of Technology (http://www.cis.hut.fi/projects/somtoolbox/).

The SOM Toolbox allows the associations between dipteran taxa and SOM regions to be visualised in the form of greyness gradients over the two-dimensional lattice [83]. This visualisation may facilitate the formulation of ecological conclusions as taxa with the same patterns of greyness usually co-occurred and exhibited similar habitat preferences.

However, the SOM Toolbox does not provide a statistical verification of those associations. For this reason, the untransformed dipteran abundance data were subjected to Indicator Species Analysis (ISA): the associations between each dipteran taxon and each subcluster of output neurons, and its respective environmental conditions, were expressed in a numeric form with the indicator values (IndVals) [88]. IndVals complement the visualisation in the form of greyness gradients. An IndVal (range 0-100%) of taxon i in all real DCSs of subcluster j is a product of three variables: (1) A_{ij} – a measure of specificity, i.e. the mean abundance of taxon i in real DCSs assigned to subcluster j divided by the sum of its average abundances in all subclusters (%), (2) F_{ij} – a measure of fidelity, i.e. the frequency of occurrence of taxon i (%) in real DCSs assigned to subcluster j, and (3) the constant 100 in order to produce the percentages:

$$\mathrm{IndVal}_{ij} = A_{ij} \times F_{ij} \times 100$$

$$A_{ij} = \text{taxon abundance}_{ij} / \text{taxon abundance}_{i.}$$

$$F_{ij} = \text{N real core samples}_{ij} / \text{N real core samples}_{.j}$$

The maximum IndVal (100%) was observed when all real DCSs with taxon i were assigned to subcluster j and when taxon i was present in all real DCSs assigned to subcluster j [88]. Significant maximum IndVals, and therefore significant associations of individual taxa with a given SOM subcluster (and its respective environmental conditions), were identified with Monte Carlo randomisation statistics. The significance level was calculated as the proportion of randomised trials with IndVal exceeding or equal to the observed IndVal. The above calculations were performed in PC-ORD [89].

Generalised linear mixed model

We asked whether chironomid taxon composition was consistent across sediment cores, so that results from a single core could be extrapolated across the whole site. Following Hadfield et al.

[90], we used a poisson family generalised linear mixed model (GLMM) with log link to test whether relative species abundances differed between cores RP W1, RP W3(2) and RP W3(4). Core RP F2 was excluded due to low temporal overlap of RP F2 sample ages with other cores, particularly core RP W1 (Fig. 2). Three samples with no age estimate from radiocarbon dating were excluded. Chironomid morphotypes that were absent from a core, age category, or sample were included as zero counts. After reducing samples to only those with strongly overlapping ages among the three cores, sample age was converted to a factor with 6 levels, to allow for nonlinearities in changes in species abundance over time. All resulting age categories were represented by all studied cores. This resulted in a dataset with 5141 individual species counts.

The response variable in the generalised linear mixed model (GLMM) was the untransformed count of individuals of each chironomid morphotype in each sample. To control for variation in sediment volume among samples, we included ln(sample volume cm^3) as an offset (logged because we fit a poisson model with log link), so that the fixed effect parameter estimates represented the effects of predictors on chironomid counts per unit sediment volume. Fixed effect predictors included core, chironomid taxon, and their interaction. Sample age category and its pairwise interactions with core and morphotype were included as random effects to control for temporal variation in abundances. The core:(morpho)species interaction fixed effect therefore tested for differences among cores in relative species abundance, controlling for differences in overall abundance among cores and morphospecies (fixed main effects), sample volume (offset), and any influence of sample age (random effects). All analyses were run in R version 4.1.2 [91]. GLMM was performed using the R package glmmTMB [92]. Model diagnostics were performed in DHARMa [93], and fixed effect model selection based on AICc carried out in MuMIn [94]. All random effects were included in every model.

Post-hoc comparison of relative species abundance differences among cores for individual chironomid morphotypes, based on the estimated core:morphospecies interaction, were carried out in the R package phia [95]. This package is not compatible with mixed effects models and so these analyses are based on a GLM model including fixed effects only, run using base R’s glm function.

Canonical Correspondence Analysis

Because the performed DCA for all four combined cores dataset revealed long biological data gradients (4.499 on Ax 1 and 4.787 on Ax 2 [SD units]), Canonical Correspondence Analysis (CCA) was selected to compare geochemical and biotic variable patterns. Due to autocorrelation, Na and Mg content were excluded from the further analysis. The CCA was performed on square-root transformed data with downweighting rare taxa, biplot scaling and inter-sample distance. The significance of environmental variables relating to the biota was tested with the Monte Carlo permutation with automatic selection and permutation under full model.

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Contributions

OA-O developed the concept of the paper, conceived the study, and contributed chironomid data. DO contributed geochemical data. AK and RIB provided statistical analyses. PK supervised the project, analysed lithology of the cores and the geomorphology of the area. PK and JS conducted the fieldwork at the study site. JS analysed the archaeological context. MK provided radiocarbon and dendrological dates. OA-O, PK, DO and MP interpreted the data and wrote the manuscript with contributions from all authors. OA-O, JS, DO and PK created the figures and tables. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Data Availability Statement

The datasets analysed during the current study are available from the corresponding author on reasonable request.

References

1. Kirilova, E.P., Cremer, H., Heiri, O., & Lotter, A.F. Eutrophication of moderately deep Dutch lakes during the past century: flaws in the expectations of water management? *Hydrobiologia* **637**, 157–171 (2010).
2. Scharf, B. & Viehberg, F.A. Living Ostracoda (Crustacea) from the town moat of Bremen, Germany. *Crustaceana* **87(8–9)**, 1124–1135 (2014).
3. Rees, S.E. The historical and cultural importance of ponds and small lakes in Wales, UK. *Aquat. Conserv.* **7(2)**, 133–139 (1997).

4. Brown, A. *et al.* The ecological impact of conquest and colonisation on a medieval frontier landscape: combined palynological and geochemical analysis of lake sediments from Radzyń Chełmiński, northern Poland. *Geoarchaeology* **30**, 511–527 (2015).
5. Kittel, P. *et al.* The palaeoecological development of the Late Medieval moat – Multiproxy research at Rozprza, Central Poland. *Quat. Int.* **482**, 131–156 (2018).
6. Hildebrandt-Radke, I. Geoarchaeological aspects in the studies of prehistoric and early historic settlement complexes in *Studia interdyscyplinarne nad środowiskiem i kulturą w Polsce. Tom 1. Środowisko-Człowiek-Cywilizacja* (eds. Makohonienko, M., Makowiecki, D. & Kurnatowska, Z.) 57-70 (Bogucki Wyd. Naukowe, 2007).
7. Łyszkowski, M. & Wardas-Lasoń, M. Georadar investigations and geochemical analysis in contemporary archaeological studies. *Geology, Geophysics & Environment* **38(3)**, 307–315 (2012).
8. Korhola, A. & Rautio, M. Cladocera and other branchiopod crustaceans in *Tracking environmental change using lake sediments, Vol. 4: Zoological indicators* (eds. Smol, J.P., Birks, H.J.B., Last, W.M.) 5–41 (Kluwer Academic Publishers, 2001).
9. Birks, H.H. Plant macrofossils in *Tracking environmental change using lake sediments, Vol. 3: Terrestrial, algal, and siliceous indicators* (eds. Smol, J.P., Birks, H.J.B. & Last, W.M.) 49–74 (Kluwer Academic Publishers, 2001).
10. Battarbee, R.W. Diatom analysis in *Handbook of Holocene paleoecology and paleohydrology* (ed. Berglund, B.E.), 527–570 (John Wiley and Sons, 1986).
11. Luoto, T.P., Nevalainen, L., Kultti, S. & Sarmaja-Korjonen, K. An evaluation of the influence of water depth and river inflow on quantitative Cladocera-based temperature and lake level inferences in a shallow boreal lake. *Hydrobiologia* **676**, 143–154 (2011).
12. Luoto, T.P. Intra-lake patterns of aquatic insect and mite remains. *J. Paleolimnol.* **47**, 141–157 (2012).
13. Hann, B.J. Cladocera. Methods in Quaternary Ecology. *Geosci. Canada* **16**, 17–26 (1989).
14. Dimbleby, G.W. *The Palynology of Archaeological Sites* (Academic Press, Inc., 1985).
15. Edwards, K.J. Using space in cultural palynology: the value of the off-site pollen record in *Modelling ecological change: perspectives from neoecology, palaeoecology and environmental archaeology* (eds. Harris, D.R. & Thomas, K.D.) 61–74 (Routledge Taylor & Francis Group, 2016).

16. Kittel, P., Sikora, J. & Wroniecki, P. A Late Medieval motte-and-bailey settlement in a lowland river valley landscape of central Poland. *Geoarchaeology* **33(5)**, 558–578 (2018).
17. Antczak-Orlewska, O. *et al.* The environmental history of the oxbow in the Luciąża River valley – Study on the specific microclimate during Allerød and Younger Dryas in central Poland. *Quat. Int.*; 10.1016/j.quaint.2021.08.011 (2021).
18. Dearing, J.A. Core correlation and total sediment influx in *Handbook of Holocene paleoecology and paleohydrology* (ed. Berglund, B.E.) 247–270 (John Wiley and Sons, 1986).
19. O'Brien, C. *et al.* A sediment-based multiproxy palaeoecological approach to the environmental archaeology of lake dwellings (crannogs), central Ireland. *Holocene* **15**, 707–719 (2005).
20. Ruiz, Z., Brown, A.G. & Langdon, P.G. The potential of chironomid (Insecta: Diptera) larvae in archaeological investigations of floodplain and lake sediments. *J. Archaeol. Sci.* **33**, 14–33 (2006).
21. Kittel, P. *et al.* A multi-proxy reconstruction from Lutomiersk-Koziówki, Central Poland, in the context of early modern hemp and flax processing. *J. Archaeol. Sci.* **50**, 318–337 (2014).
22. Kittel, P., *et al.* On the border between land and water: the environmental conditions of the Neolithic occupation from 4.3 until 1.6 ka BC at Serteya, Western Russia. *Geoarchaeology* **36**, 173–202 (2021).
23. Makohonienko, M. *et al.* Environmental changes during Mesolithic-Neolithic transition in Kuyavia Lakeland, Central Poland. *Quat. Int.*; 10.1016/j.quaint.2021.11.020 (2021).
24. Porinchu, D.F. & MacDonald, G.M. The use and application of freshwater midges (Chironomidae: Insecta: Diptera) in geographical research. *Prog. Phys. Geogr.* **27**, 378–422 (2003).
25. Brooks, S.J., Langdon, P.G. & Heiri, O. *The identification and use of Palaearctic Chironomidae larvae in palaeoecology.* QRA Technical guide no. 10 (Quaternary Research Association, 2007).
26. Solon, J. *et al.* Physico-geographical mesoregions of Poland: Verification and adjustment of boundaries on the basis of contemporary spatial data. Geogr. Pol. **91(2)**, 143–170 (2018).
27. Kittel, P., Sikora, J., & Wroniecki, P. The morphology of the Luciąża River valley floor in the vicinity of the Rozprza medieval ring-fort in light of geophysical survey. *Bull. Geogr. Phys. Geogr. Ser.* **8**, 95–106 (2015).

28. Hingham, R., Barker, P., 2002. Timber castles, University of Exeter Press, Exeter.

29. Marciniak-Kajzer, A. Archaeology on medieval knights’ manor houses in Poland (Wyd. Uniwersytetu Łódzkiego, Wyd. Uniwersytetu Jagiellońskiego, 2016).

30. Moller Pillot, H.K.M. *Chironomidae larvae of the Netherlands and adjacent lowlands. Biology and ecology of the aquatic Orthocladiinae, Prodiamesinae, Diamesinae, Buchonomyiinae, Podonominae, Telmatogetoninae* (KNNV Publishing, 2013).

31. Luoto, T.P. An assessment of lentic ceratopogonids, ephemeropterans, trichopterans and oribatid mites as indicators of past environmental change in Finland. *Ann. Zool. Fenn.* **46**, 259–270 (2009).

32. Cierniewski, J. Spatial complexity of the Cybina river valley organic soils against the background of physiographic conditions. *Soil Sci. Annu.* **32(4)**, 3–51 (1981).

33. Rydelek, P. Origin and composition of mineral constituents of fen peat from Eastern Poland. *J. Plant Nutr.* **36(6)**, 911–928 (2013).

34. Wachecka-Kotkowska, L. Rozwój rzeźby obszaru między Piotrkowem Trybunalskim, Radomskiem a Przedborzem w czwartorzędzie (Wyd. Uniwersytetu Łódzkiego, 2015).

35. Ciszewski, D. Pollution of Mała Panew river sediments by heavy metals: Part I. Effect of changes in river bed morphology. *Pol. J. Environ. Stud.* **13(6)**, 589–595 (2004).

36. Borówka, R. Late Vistulian and Holocene denudation magnitude in morainic plateaux: case studies in the zone of maximum extent of the last ice sheet. *Quaternary Studies in Poland* **9**, 5–31 (1990).

37. Prusinkiewicz, Z., Bednarek, R., Kośko, A. & Szmyt, M. Palaeopedological studies of the age and properties of illuvial bands at an archaeological site. *Quat. Int.* **51/52**, 195–201 (1998).

38. Sowiński, P. Variability of the content of marcoelements in soils of a young glacial river valley - a geochemical landscape approach. *J. Elem.* **21(4)**, 1348–1358 (2016).

39. Kühtreiber, T. The medieval castle Lanzenkirchen in Lower Austria: reconstruction of economical and ecological development of an average-sized manor (12th-15th century). *Archaeol. Pol.* **17**, 135–144 (1999).

40. Kočár, P., Čech, P., Kozáková, R. & Kočárová, R. Environment and economy of the early medieval settlement in Žatec. *Interdiscip. Archaeol.* **1**, 45–60 (2010).

41. Brown, A.D. & Pluskowski, A.G. Detecting the environmental impact of the Baltic Crusades on a late medieval (13th-15th century) frontier landscape: palynological analysis from Malbork Castle and hinterland, Northern Poland. *J. Archaeol. Sci.* **38**, 1957–1966 (2011).
42. Beneš, J. *et al.* Archaeobotany of the Old Prague Town defence system, Czech Republic: archaeology, macro-remains, pollen, and diatoms. *Veg. Hist. Archaeobot.* **11(1/2)**, 107–119 (2002).
43. Badura, M. & Latałowa, M. Szczątki makroskopowe roślin z obiektów archeologicznych Zespołu Przedbramia w Gdańsku in *Zespół Przedbramia ul. Długiej w Gdańsku. Studium archeologiczne* (ed. Pudło, A.) 231–247 (Muzeum Historii Miasta Gdańska, 2016).
44. Dobrowolski, R. *et al.* Environmental conditions of settlement in the vicinity of the mediaeval capital of the Cherven Towns (Czermno site, Hrubieszów Basin, Eastern Poland). *Quat. Int.* **493**, 258–273 (2018).
45. Makohonienko, M. Środowisko przyrodnicze i gospodarka w otoczeniu średniowiecznego grodu w Łęczycy w świetle analizy palinologicznej in *Początki Łęczycy. Tom I – Archeologia środowiskowa średniowiecznej Łęczycy. Przyroda–Gospodarka–Społeczeństwo* (eds. Grygiel, R. & Jurek, T.) 95–190 (MAiE w Łodzi, 2014).
46. Koszałka, J. Źródła archeobotaniczne do rekonstrukcji uwarunkowań przyrodniczych oraz gospodarczych grodu w Łęczycy in *Początki Łęczycy. Tom I – Archeologia środowiskowa średniowiecznej Łęczycy. Przyroda–Gospodarka–Społeczeństwo* (eds. Grygiel, R. & Jurek, T.) 191–241 (MAiE w Łodzi, 2014).
47. Digerfeldt, G. 1986. Studies on past lake-level fluctuations in *Handbook of Holocene paleoecology and paleohydrology* (ed. Berglund, B.E.) 127–143 (John Wiley and Sons, 1986).
48. Magny, M. Palaeoclimatology and archaeology in the wetlands in *The Oxford handbook of wetland archaeology* (eds. Menotti, F. & O'Sullivan, A.) 585–597 (Oxford University Press, 2013).
49. Płóciennik, M. *et al.* Summer temperature drives the lake ecosystem during the Late Weichselian and Holocene in Eastern Europe: A case study from East European Plain. *Catena* (in press).
50. Święta-Musznicka, J., Badura, M., Pędziszewska, A. & Latałowa, M. Environmental changes and plant use during the 5th-14th centuries in medieval Gdańsk, northern Poland. *Veget. Hist. Archaeobot.* **30**, 363–381 (2021).

51. Rackham, J. & Sidell, J. London's landscapes: the changing environment in *The archaeology of Greater London. An assessment of archaeological evidence for human presence in the area now covered by Greater London* (ed. Kendall, M.) 12–27 (Museum of London, 2000).
52. Ledger, P., Edwards, K. & Schofield, J. A multiple profile approach to the palynological reconstruction of Norse landscapes in Greenland's Eastern Settlement. *Quat. Res.* **82(1)**, 22–37 (2014).
53. Albert, B. & Innes, J. Multi-profile fine-resolution palynological and micro-charcoal analyses at Esklets, North York Moors, UK, with special reference to the Mesolithic-Neolithic transition. *Veget. Hist. Archaeobot.* **24**, 357–375 (2015).
54. Sikora, J., Kittel, P. & Wroniecki, P. From a point on the map to a shape in the landscape. Non-invasive verification of medieval ring-forts in Central Poland: Rozprza case study. *Archaeol. Pol.* **53**, 510–514 (2015).
55. Sikora, J. *et al.* A palaeoenvironmental reconstruction of the rampart construction of the medieval ring-fort in Rozprza, Central Poland. *Archaeol. Anthropol. Sci*. **11(8)**, 4187–4219 (2019).
56. Tolksdorf, J.F., Turner, F., Nelle, O., Peters, S. & Bruckner H. Environmental development and local human impact in the Jeetzel valley (N Germany) since 10 ka BP as detected by geoarchaeological analyses in a coupled aeolian and lacustrine sediment archive at Soven. *E&G Quaternary Sci. J.* **64**, 95–110 (2015).
57. Clift, P.D. *et al.* Grain-size variability within a mega-scale point-bar system, False River, Louisiana. *Sedimentology* **66**, 408–434 (2019).
58. Blott, S.J. & Pye, K. GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surf. Process. Landf.* **26**, 1237–1248 (2001).
59. Rolland, N. & Larocque, I. The efficiency of kerosene flotation for extraction of chironomid head capsules from lake sediments samples. *J. Paleolimnol.* **37**, 565–572 (2007).
60. Schmid, P.E. *A key to the Chironomidae and their instars from Austrian Danube region streams and rivers. Part I. Diamesinae, Prodiamesinae and Orthocladiinae* (Federal Institute for Water Quality of the Ministry of Agriculture and Forestry, 1993).
61. Andersen, T., Cranston, P.S. & Epler, J.H. *Chironomidae of the Holarctic Region: Keys and diagnoses. Part 1. Larvae.* Insect Systematics and Evolution Supplements 66 (Scandinavian Entomology, 2013).

62. Vallenduuk, H.J. & Moller Pillot, H.K.M. *Chironomidae larvae of the Netherlands and adjacent lowlands. General ecology and Tanypodinae* (KNNV Publishing, 2007).

63. Moller Pillot, H.K.M. *Chironomidae larvae. Biology and ecology of the Chironomini* (KNNV Publishing, 2009)

64. Juggins, S. *C2 version 1.5 user guide. Software for ecological and palaeoecological data analysis and visualisation* (Newcastle University, 2007)

65. Schweingruber, F.H. *Tree rings. Basics and applications of dendrochronology* (Kluwer Academic Publishers, 1988).

66. Skripkin, V.V. & Kovalyukh, N.N. Recent developments in the procedures used at the SSCER Laboratory for the routine preparation of lithium carbide. *Radiocarbon* **40(1)**, 211–214 (1998).

67. Krąpiec, M. & Walanus, A. Application of the triple photomultiplier liquid spectrometer Hidex 300SL in radiocarbon dating. *Radiocarbon* **53**, 543–550 (2011).

68. Nadeau, M.-J. *et al.* Sample throughput and data quality at the Leibniz-Labor AMS facility. *Radiocarbon* **40(1)**, 239–245 (1998).

69. Krąpiec, M., Rakowski, A.Z., Huels, M., Wiktorowski, D. & Hamann, C. A new graphitization system for radiocarbon dating with AMS on the dendrochronological laboratory at AGH-UST Kraków. *Radiocarbon* **60(4)**, 1091–1100 (2018).

70. Cherkinsky, A., Culp, R.A., Dvoracek, D.K. & Noakes, J.E. Status of the AMS facility at the University of Georgia. *Nucl. Instrum. Methods Phys. Res. B* **268(7–8)**, 867–870 (2010).

71. Zoppi, U., Crye, J., Song, Q. & Arjomand, A. Performance Evaluation of the New AMS System at Accium Biosciences. *Radiocarbon* **49**, 173–182 (2007).

72. Reimer, P. *et al.* The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* **62(4)**, 725–757 (2020).

73. Bronk Ramsey, C. OxCal version 4.4.2. Available at: https://c14.arch.ox.ac.uk (2020).

74. Bronk Ramsey, C. Bayesian analysis of radiocarbon dates. *Radiocarbon* **51(1)**, 337–360 (2009).

75. Bronk Ramsey, C. Deposition models for chronological records. *Quat. Sci. Rev.* **27(1-2)**, 42–60 (2008).

76. Kohonen, T. Self-organized formation of topologically correct feature maps. *Biol. Cybern.* **43**, 59–69 (1982).

77. Kohonen, T. Self-organizing maps (Springer-Verlag, 2001).

78. Park, Y.-S. *et al.* Application of a self-organizing map to select representative species in multivariate analysis: a case study determining diatom distribution patterns across France. *Ecol. Inform.* **1**, 247–257 (2006).

79. Zhang, Q. *et al.* Self-organizing feature map classification and ordination of *Larix principis-rupprechtii* forest in Pangquangou Nature Reserve. *Acta Ecol. Sin.* **31**, 2990–2998 (2011).

80. Ney, J.J. Practical use of biological statistics in *Inland Fisheries Management in North America* (eds. Kohler, C.C., Bethesda, M.D. & Hubert, W.A.) 137–158 (American Fisheries Society, 1993).

81. Płóciennik M. *et al.* Fen ecosystem responses to water-level fluctuations during the early and middle Holocene in central Europe: a case study from Wilczków, Poland. *Boreas* **44(4)**, 721–740 (2015).

82. Brosse, S., Giraudel, J.L. & Lek, S. Utilisation of non-supervised neural networks and principal component analysis to study fish assemblages. *Ecol. Modell.* **146(1)**, 159–166 (2001).

83. Lek, S., Scardi, M., Verdonschot, P.F.M., Descy, J.P. & Park, Y.S. *Modelling community structure in freshwater ecosystems* (Springer-Verlag, 2005).

84. Quinn, G.P. & Keough, M. *Experimental design and data analysis for biologists* (University of Cambridge, 2002).

85. Vesanto, J. & Alhoniemi, E. Clustering of the self-organizing map. *IEEE Trans. Neural Netw.* **11**, 586–600 (2000).

86. Ward, J.H. Hierarchical grouping to optimize an objective function. *J. Am. Stat. Assoc.* **58**, 236–244 (1963).

87. Alhoniemi, E., Hollmén, J., Simula, O. & Vesanto, J. Process monitoring and modeling using the self-organizing map. *Integr. Comput. Aided Eng.* **6(1)**, 3–14 (1999).

88. Dufrêne, M. & Legendre, P. Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecol. Monogr.* **67**, 345–356 (1997).

89. McCune, B. & Mefford, M.S. PcOrd Multivariate Analysis of Ecological Data. Version 6.06 (MjM Software, 2011).

90. Hadfield, J.D., Krasnov, B.R., Poulin, R. & Nakagawa, S. A tale of two phylogenies: comparative analyses of ecological interactions. *Am. Nat.* **183(2)**, 174-187 (2014).

91. R Core Team. *R: A language and environment for statistical computing* (R Foundation for Statistical Computing, 2021). https://www.R-project.org/

92. Brooks, M.E. et al. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *R Journal* **9(2)**, 378–400 (2017).

93. Hartig, F. DHARMa: residual diagnostics for hierarchical (multi-level/mixed) regression models. R package version 0.4.5. https://CRAN.R-project.org/package=DHARMa (2022).

94. Barton, K. MuMIn: Multi-Model Inference. R package version 1.43.17. https://CRAN.R-project.org/package=MuMIn (2020).

95. de Rosario-Martinez, H. phia: post-hoc interaction analysis. R package version 0.2-1. https://CRAN.R-project.org/package=phia (2015).

Table 1. The results of radiocarbon dating of the organic deposits of Rozprza moats.

Core	Lithology	Depth (cm b.g.l.)	Laboratory code /dating method	Dated material	^{14}C age (yr BP)	Calibrated age (cal AD)	
						68.2%	95.4%
RP W3(2)	top of overbank organic mud	42-47	MKL-2839/LST	overbank deposits bulk	120±40	1690-1922	1647-1943
	top of peat	55-60	MKL-2840/LST	peat bulk	230±35	1641-1800	1525-…
	peat	75-80	MKL-2841/LST	peat bulk	320±40	1506-1639	1472-1650
	peat/coarse detritus gyttja	85-90	MKL-2842/LST	gyttja bulk	370±35	1458-1622	1449-1635
	upper part of coarse detritus gyttja	92-94	MKL-3504A/AMS	*Rubus idaeus* – 2 seeds *Solanum nigrum* – 1 seed	409±36	1440-1615	1428-1629
	bottom of clayey coarse detritus gyttja	130-135	MKL-2843/LST	gyttja bulk	1280±50*	667-773*	656-877*
	sand with plant detritus	134-136	D-AMS 016324 /AMS	*Rumex* sp. – 2 inflorescences *Chenopodium rubrum* – 1 leaf *Urtica dioica* – 2 leaves	715±43	1265-1380	1225-1390
RP W3(4)	top of overbank organic mud	38-43	MKL-2958/LST	overbank deposits bulk	100±40	1694-1918	1680-1939
	peat	50-55	MKL-2957/LST	peat bulk	200±40	1655-1950	1642-1950
	peat/coarse detritus gyttja	60-65	MKL-2956/LST	gyttja bulk	460±40	1417-1455	1401-1616
	bottom of clayey coarse detritus gyttja	75-80	MKL-2955/LST	gyttja bulk	1190±60*	710-950*	681-990*

Table 1. Continued.

Core	Lithology	Depth (cm b.g.l.)	Laboratory code /dating method	Dated material	^{14}C age (yr BP)	Calibrated age (cal AD)	
						68.2%	95.4%
RP W1	bottom of muddy peat	20-22	MKL-A5577/AMS	*Urtica dioica* – 5 fruits *Mentha arvensis* – 1 fruit *Thalictrum flavum* – 1 fruit *Carex flava* – 15 fruits *Sambucus* sp. – 1 seed	479±22	1425-1442	1414-1450
	bottom of peat	40-45	MKL-2609/LST	peat bulk	610±50	1305-1397	1289-1415
RP F2	bottom of sandy organic mud	38-43	MKL-2966/LST	organic deposits bulk	80±40	1695-1916	1683-1936
	bottom of peat	60-65	MKL-2967/LST	peat bulk	340±50	1484-1634	1455-1646

* date recognised as outlier (redeposited material), not included in age-depth model

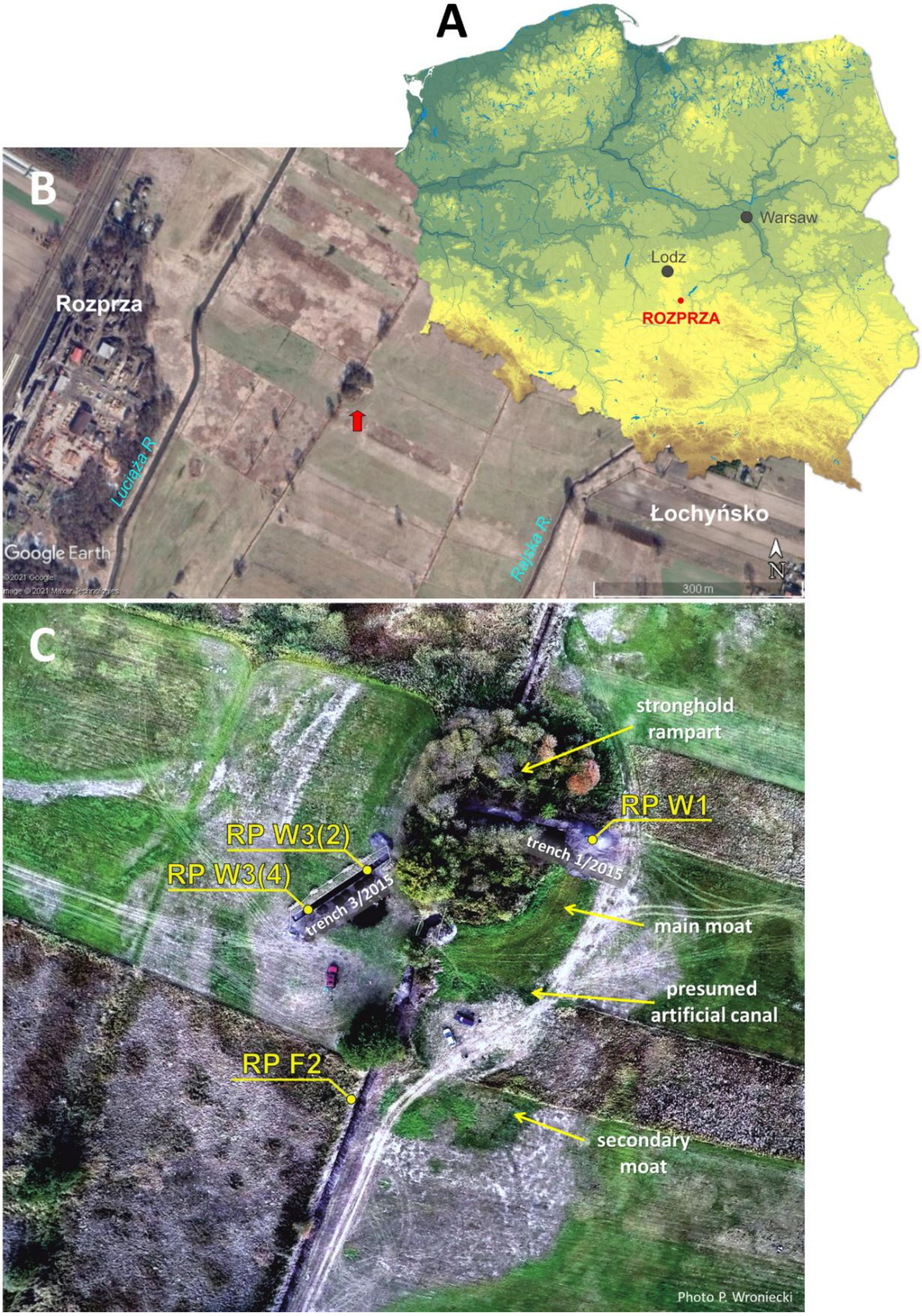


Figure 1. A – Study site location in the territory of Poland. B – The satellite picture of the contemporary surroundings of the study area. The red arrow indicates the stronghold's remnants (source: Google Earth, modified). C – Aerial photo of the study area. The locations of the studied profiles (cores) are marked by yellow dots. Arrows indicate the traces of artificial elements visible in the terrain relief (photo: P. Wroniecki, 2015).

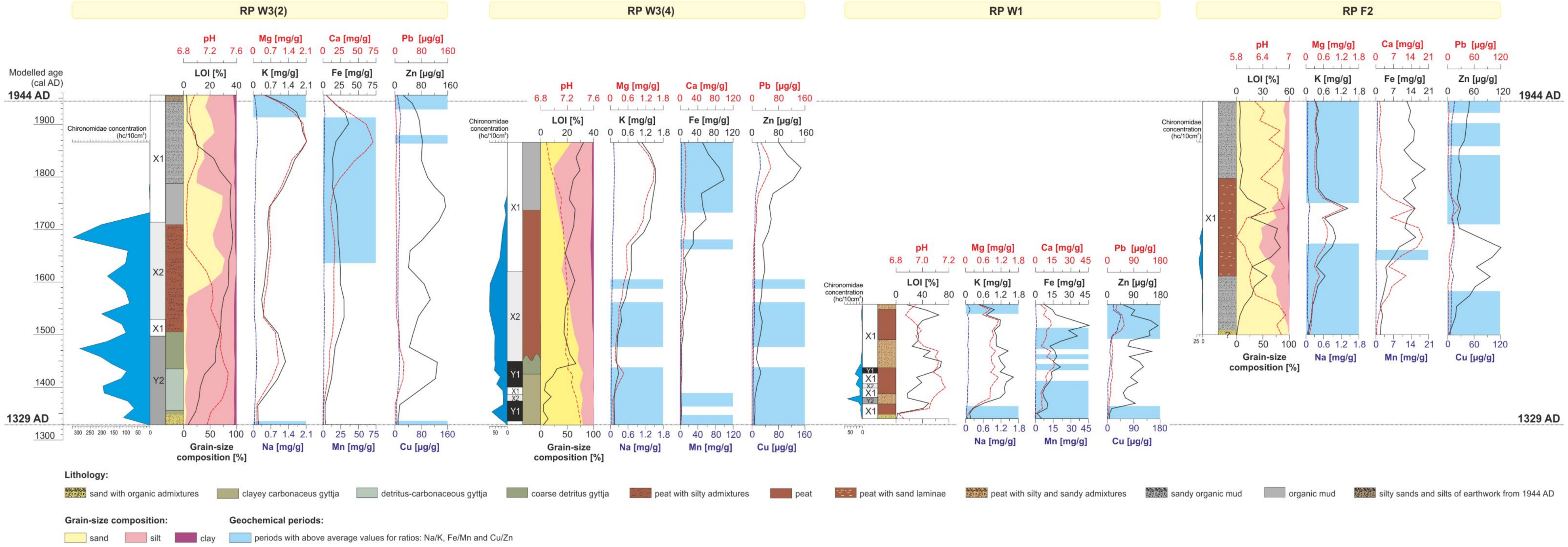


Figure 2. Core correlation with reference to: modelled chronology, Chironomidae-inferred SOM subcluster zones (symbols are used as in the Fig. 3), lithology, grain-size composition, lithogeochemical results and statistical relations of selected elements. Question mark means uncertain date of the secondary moat establishment. Geochemical periods were designated on the variable results with respect to average values Na/K (mean=0.12), Fe/Mn (mean=60) and Cu/Zn (mean=0.27) ratios.

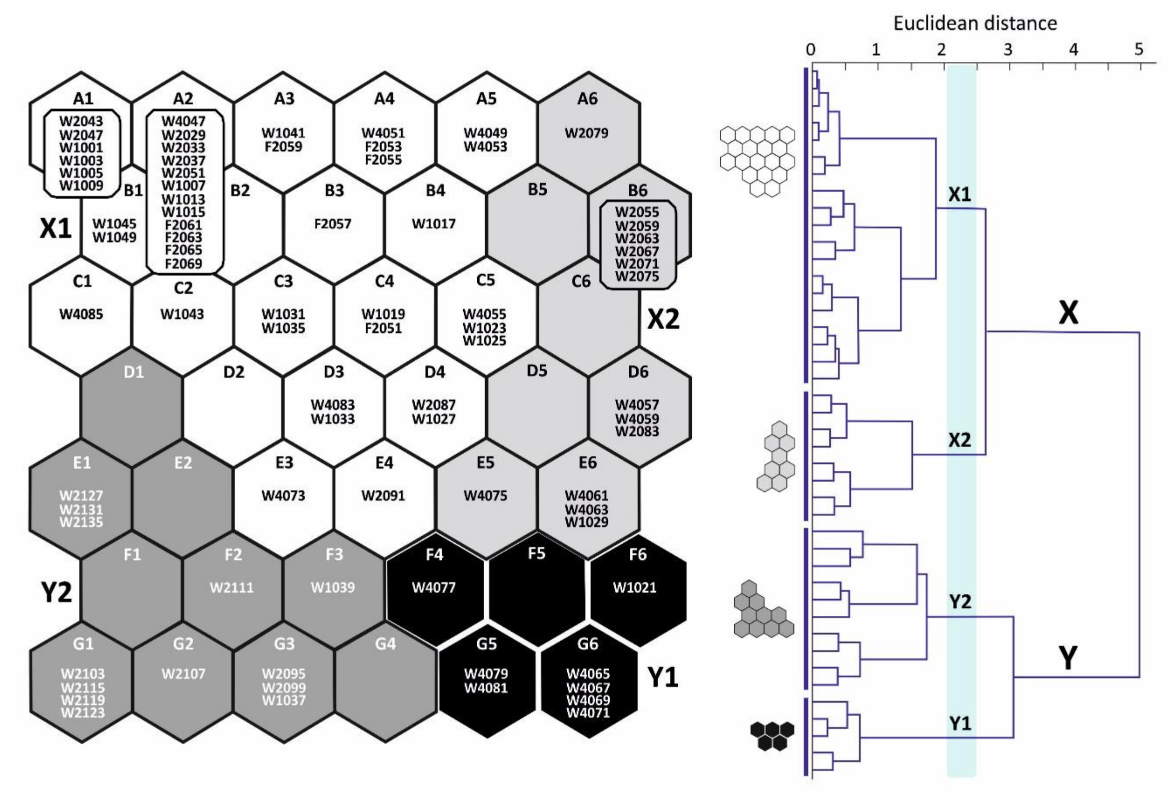


Figure 3. Seventy nine non-empty core samples assigned to 42 self-organising map (SOM) output neurons (A1–G7). The neurons are arranged into a two-dimensional lattice (7×6). Clusters (X and Y) and subclusters (X1, X2, Y1 and Y2; shown in different degrees of greyness) of neurons have been identified with the use of hierarchical cluster analysis. Sample codes are arranged as follows: first two signs stand for core symbol (W1 – RP W1, W2 – RP W3(2), W4 – RP W3(4), F2 – RP F2), followed by numbers referring to depth (in cm b.g.l.).

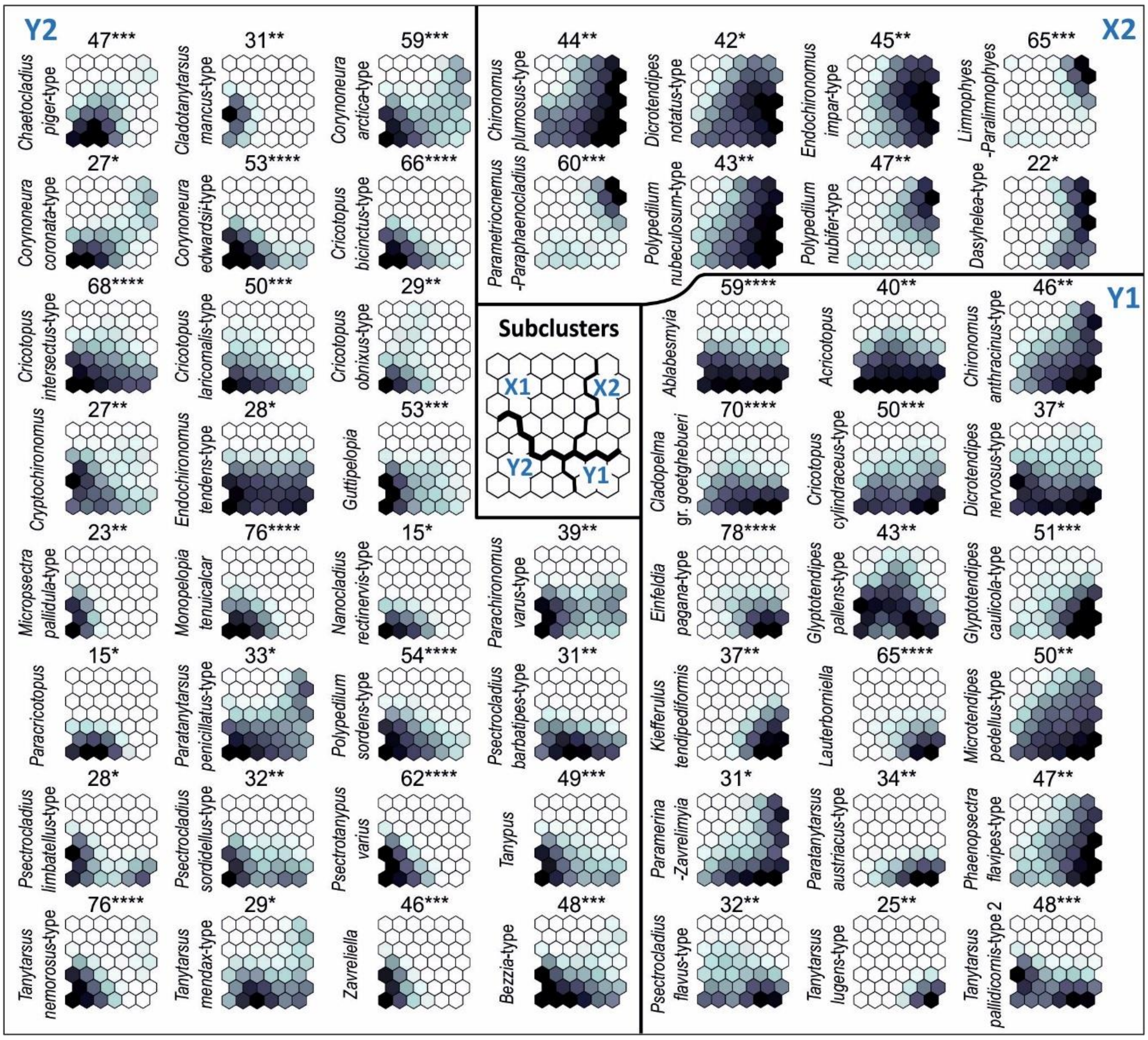
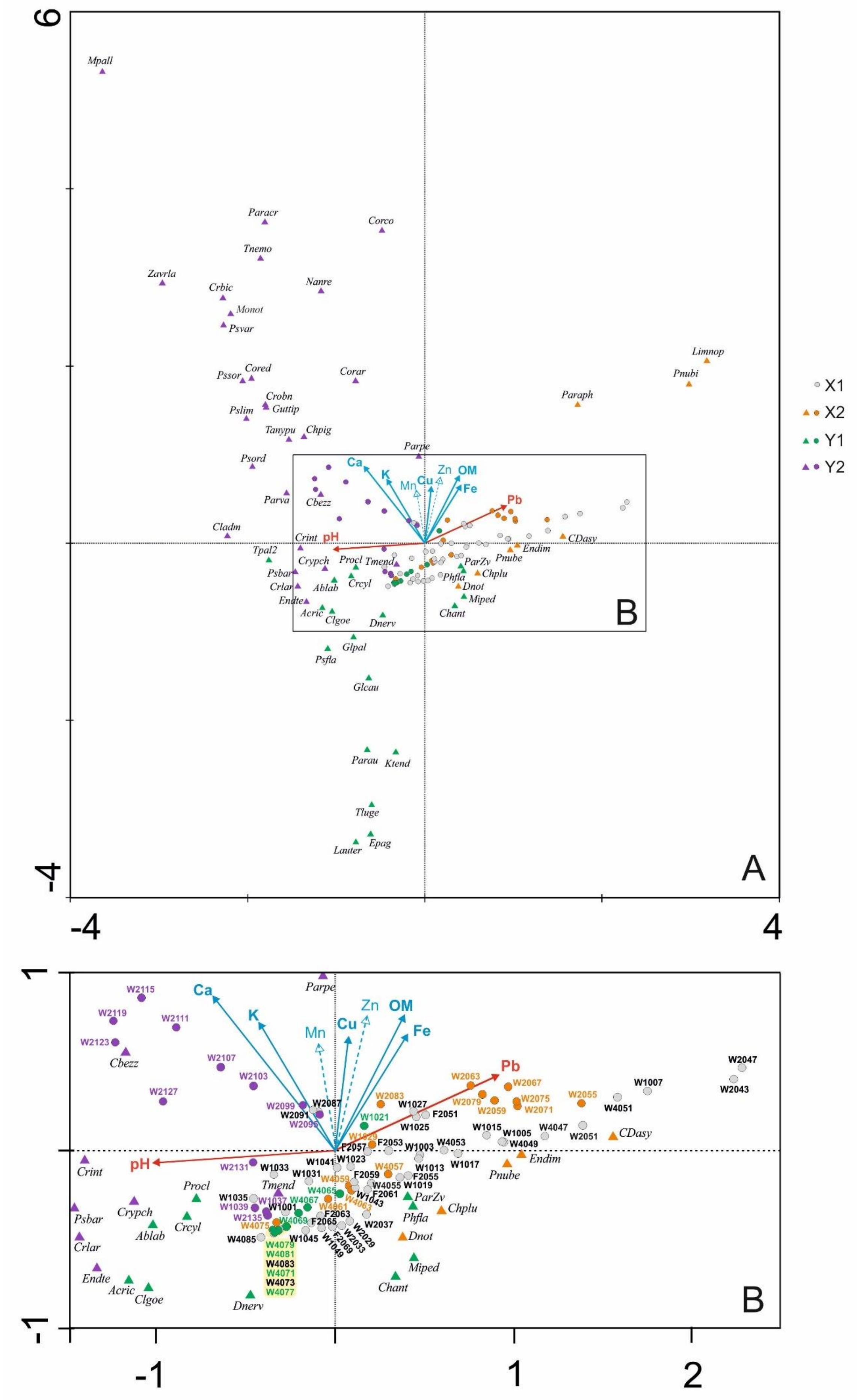


Figure 4. Fifty five dipteran taxa significantly ($p \le 0.05$) associated with SOM subclusters X2, Y1 and Y2 (respectively, 8, 19 and 28 taxa). No palaeoindicator was significantly associated with subcluster X1. The shading is scaled independently for each taxon; it is darker for a stronger association in virtual core samples. Maximum observed indicator value (IndVal) is shown above each taxon plane; IndVals and their significance levels were calculated on the basis of real core samples. The plane for *Procladius* (56***), which is indicative of subcluster Y1, is not presented for graphical reasons; it resembles the plane for *Ablabesmyia*.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-4
-4
4
Mpall
Paracr
Corco
Tnemo
Zavrla
Crbic
Nanre
Monot
Psvar
Limnop
Pnubi
Cored
Pssor
Corar
Paraph
Crobn
Guttip
Pslim
Tanypu
Chpig
Parpe
Psord
Ca
K
Mn
Cu
Zn
OM
Fe
Pb
Parva
Cbezz
Cladm
Crint
pH
CDasy
Endim
Tpal2
Crypch
Procl
Tmend
Pnube
ParZv
Psbar
Chplu
Phfla
Crlar
Ablab
Crcyl
Dnot
Endte
Miped
Acric
Clgoe
Chant
Dnerv
Glpal
Psfla
Glcau
Parau
Ktend
Tluge
Epag
Lauter
A
B
X1
X2
Y1
Y2
1
-1
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1
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W2115
W2119
W2111
W2123
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W2103
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W4075
W4085
W1045
W1049
F2069
W2033
W2029
W4079
W4081
W4083
W4071
W4073
W4077
B

←Figure 5. CCA biplot showing changes in the moat states expressed by SOM subclusters represented by indicative Chironomidae taxa (triangles) and sediment samples (circles), under a gradient of environmental variables (A). Variables correlated with Ax1 are shown as red arrows, while those correlated with Ax2 are shown as blue arrows. Mn and Zn were not significant for the analysis. Taxa and samples associated with each subcluster are coloured differently. Sample codes given on zoom (B) are arranged as follows: first two signs stand for core symbol (W1 – RP W1, W2 – RP W3(2), W4 – RP W3(4), F2 – RP F2), followed by numbers referring to depth (in cm b.g.l.). For full names of taxa see Supplementary Table S5.

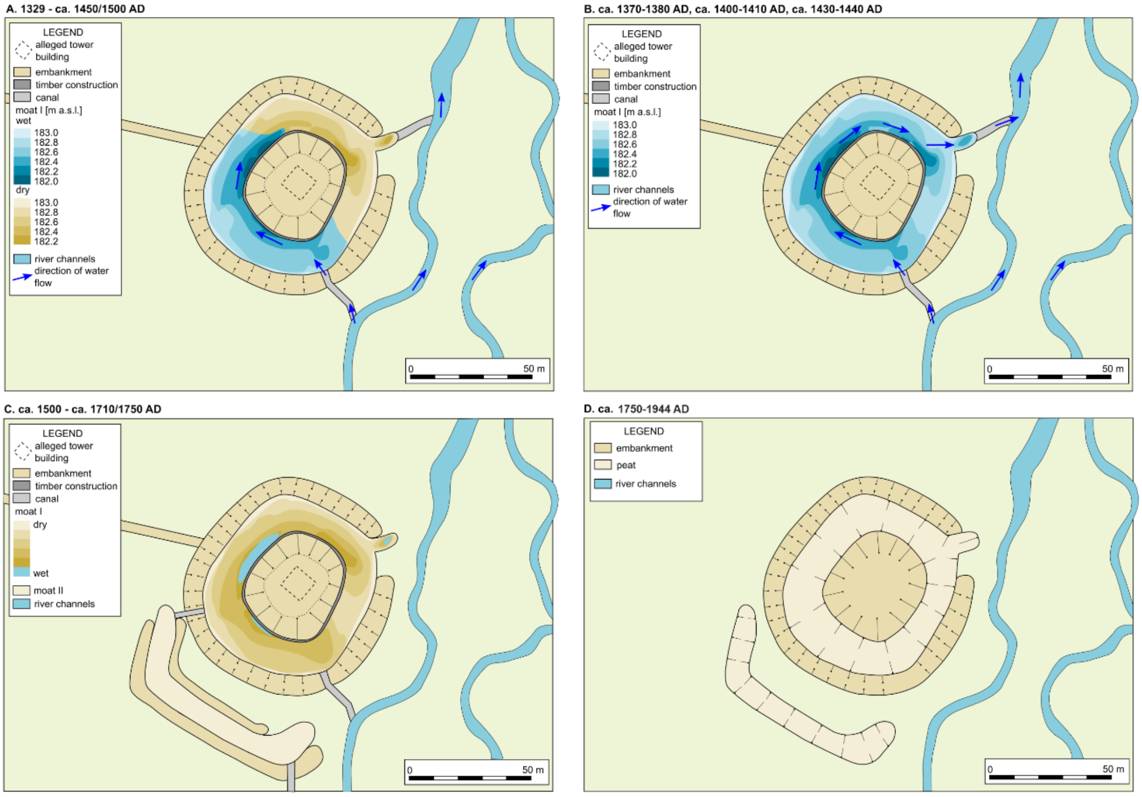


Figure 6. Phases and episodes of different moat states over time: A – limnetic stage only in the southern (deeper) part of the main moat (1329 - ca. 1450/1500 AD); B – limnetic stage in the whole main moat, episodes of higher water level in the NE part of the moat, indicated by Y2, X2 and Y1 subclusters in the core RP W1 (ca. 1370-1380 AD, ca. 1400-1410 AD, ca. 1430-1440 AD); C – construction of the southern secondary moat, telmatic stage (ca. 1500 - ca. 1710/1750 AD); D – terrestrial stage in the both moats up to their covering with the material from the stronghold's mound in 20th century AD (ca. 1750 - 1944 AD).

Supplementary information

Supplementary Table S1. The P_Sequence depth/age model for the RP W3(2) core. Indices: A_{model} = 63.1, $A_{overall}$ = 63.7.

Name	Depth (cm b.g.l.)	^{14}C age (yr BP)	Calibrated age (cal AD)		Modelled age (AD)		Mean age ±1σ (AD)	Indices	
			68.2%	95.4%	68.2%	95.4%		A	C
Boundary Top	0.0				1701-1914	1677-2088	1851 ± 119		95.0
R_Date 42-47	44.5	120±40	1690-1922	1647-1943	1673-1856	1667-1919	1771 ± 76	97.1	98.0
R_Date 55-60	57.5	230±35	1641-1800	1525-…	1641-1796	1635-1802	1695 ± 57	114.4	99.1
R_Date 75-80	77.5	320±40	1506-1639	1472-1650	1513-1637	1490-1645	1568 ± 45	105.0	97.6
R_Date 85-90	87.5	370±35	1458-1622	1449-1635	1460-1523	1452-1625	1517 ± 48	108.7	98.1
R_Date 92-94	93.0	409±36	1440-1615	1428-1629	1448-1502	1436-1618	1494 ± 47	104.7	99.2
R_Date 134-136	135.0	715±43	1265-1380	1225-1390	1325-1378	1325-1387	1345 ± 21	22.8	98.0
C_Date 136*	136.0				1328-1329	1328-1329	1329	100.0	100.0
Boundary Bottom	136.0				1328-1329	1328-1329	1329		100.0

OxCal v4.4.2 [73]: r.5 Atmospheric curve [72]

* dendrochronological data of wood fragment 1329 AD

Supplementary Table S2. The P_Sequence depth/age model for the RP W3(4) core. Indices: A_{model} = 98.8, $A_{overall}$ = 98.7.

Name	Depth (cm b.g.l.)	^{14}C age (yr BP)	Calibrated age (cal AD)		Modelled age (AD)		Mean age ±1σ (AD)	Indices	
			68.2%	95.4%	68.2%	95.4%		A	C
Boundary Top	0.0				1717-2051	1689-2348	1969 ± 174		97.6
R_Date 38-43	40.5	100±40	1695-1916	1679-1941	1703-1912	1681-1940	1823 ± 74	100.6	99.3
R_Date 50-55	52.5	200±40	1656-…	1640-…	1647-1796	1529-1846	1713 ± 62	104.3	99.7
R_Date 60-65	62.5	460±40	1420-1459	1401-1615	1420-1465	1404-1620	1460 ± 48	92.8	99.8
C_Date 83*	83.0				1328-1329	1328-1329	1329	100.0	100.0
Boundary Bottom	83.0				1328-1329	1328-1329	1329		100.0

OxCal v4.4.2 [73]: r.5 Atmospheric curve [72]

* dendrochronological data of wood fragment 1329 AD

Supplementary Table S3. The P_Sequence depth/age model for the RP W1 core. Indices: A_{model} = 96.8, $A_{overall}$ = 97.

Name	Depth (cm b.g.l.)	^{14}C age (yr BP)	Calibrated age (cal AD)		Modelled age (AD)		Mean age ±1σ (AD)	Indices	
			68.2%	95.4%	68.2%	95.4%		A	C
Boundary Top	0.0				1427-1570	1413-1878	1554 ± 133		96.8
R_Date 20-22	21.0	479±22	1425-1442	1414-1450	1424-1442	1413-1450	1432 ± 9	98.0	99.9
R_Date 40-45	42.5	610±50	1305-1397	1289-1415	1313-1407	1295-1421	1360 ± 36	97.8	97.7
Boundary Bottom	45.0				1309-1405	1229-1430	1340 ± 72		97.2

OxCal v4.4.2 [73]: r.5 Atmospheric curve [72]

Supplementary Table S4. The P_Sequence depth/age model for the RP F2 core. Indices: A_{model} = 98.5, $A_{overall}$ = 98.5.

Name	Depth (cm b.g.l.)	^{14}C age (yr BP)	Calibrated age (cal AD)		Modelled age (AD)		Mean age ±1σ (AD)	Indices	
			68.2%	95.4%	68.2%	95.4%		A	C
Boundary Top	0.0				1749-2269	1741-2606	2121 ± 239		96.4
R_Date 38-43	40.5	80±40	1695-1916	1683-1936	1688-1909	1674-1927	1792 ± 81	98.1	99.7
R_Date 60-65	62.5	340±50	1484-1634	1455-1646	1501-1641	1459-1650	1567 ± 58	99.8	99.1
Boundary Bottom	65.0				1491-1636	1261-1794	1522 ± 127		98.4

OxCal v4.4.2 [73]: r.5 Atmospheric curve [72]

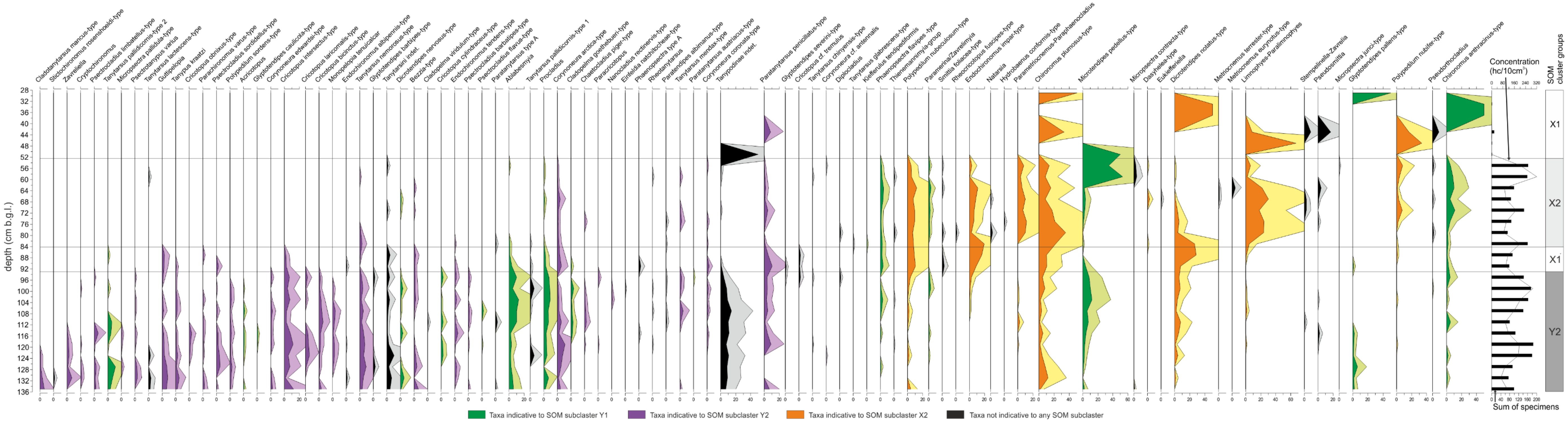
Supplementary Table S5. List of all recorded Chironomidae and Ceratopogonidae morphotypes with their codes used in CCA analysis. Relative abundance of each taxon in each of the three cores, as estimated by the core:species interaction in a generalised linear mixed model, and controlling for absolute abundance per core and taxon (fixed effects).

Full morphotype name	Morphotype code	Core		
		RP W1	RP W3(2)	RP W3(4)
Chironomus plumosus-type	Chplu	-10.18747	11.15291	-0.96544
Dicrotendipes notatus-type	Dnot	-7.17553	8.50099	-1.32546
Ablabesmyia	Ablab	-4.95403	6.34782	-1.39379
Microtendipes pedellus-type	Miped	-4.42917	2.44485	1.98432
Cricotopus intersectus-type	Crint	-4.01220	7.91084	-3.89864
Procladius	Procl	-3.99015	5.28209	-1.29193
Polypedilum nubeculosum-type	Pnube	-3.49460	1.92962	1.56498
Paratanytarsus penicillatus-type	Parpe	-2.84300	5.49873	-2.65573
Tanytarsus nemorosus-type	Tnemo	-2.58333	5.75840	-3.17508
Endochironomus impar-type	Endim	-2.39718	2.56546	-0.16828
Corynoneura arctica-type	Corar	-2.34443	5.36854	-3.02411
Limnophyes	Limnop	-1.77060	4.02722	-2.25662
Guttipelopia	Guttip	-1.13742	2.63458	-1.49716
Chironomus anthracinus-type	Chant	-0.91131	0.32552	0.58579
Tanytarsus pallidicornis-type 2	Tpal2	-0.86363	0.96176	-0.09813
Phaenopsectra flavipes-type	Phfla	-0.58267	-0.03869	0.62135
Cricotopus bicinctus-type	Crbic	-0.57186	1.60563	-1.03377
Cricotopus laricomalis-type	Crlar	-0.33296	1.21577	-0.88281
Psectrocladius sordidellus-type	Pssor	-0.30111	0.87541	-0.57430
Tanypus	Tanypu	-0.26548	0.77649	-0.51100
Bezzia-type	CBezz	-0.19722	0.94785	-0.75063
Parametriocenmus-Paraphaenocladius	Paraph	-0.16687	0.79210	-0.62523
Cricotopus cylindraceus-type	Crcyl	-0.14776	-0.24509	0.39285
Endochironomus tendens-type	Endte	-0.12772	0.21006	-0.08234
Cladopelma goetghebueri-type	Clgoe	-0.12254	-0.38209	0.50463
Monopelopia tenuicalcar	Monot	-0.00378	0.73764	-0.73386
Polypedilum sordens-type	Psord	0.02056	0.33067	-0.35123

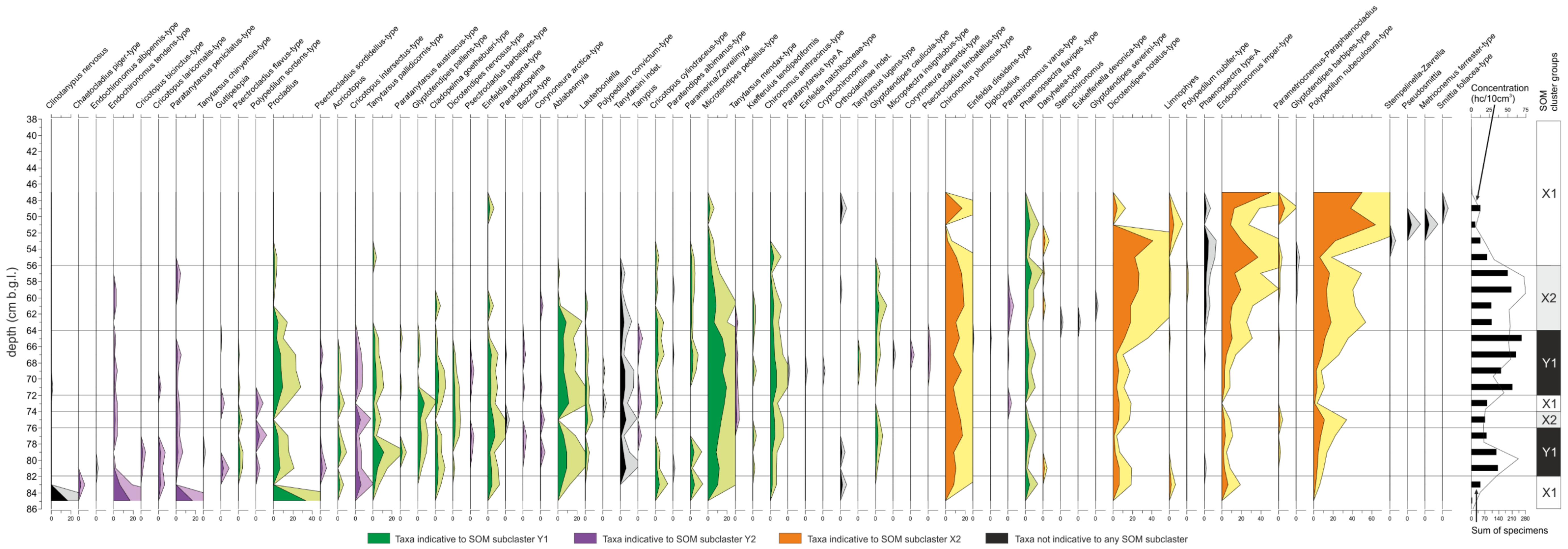
Glyptotendipes pallens-type	Glpal	0.04143	-0.16657	0.12514
Tanytarsus pallidicornis-type 1	Tpal1	0.05388	0.56263	-0.61651
Paramerina-Zavrelimyia	ParZv	0.14617	-0.81379	0.66761
Dicrotendipes nervosus-type	Dnerv	0.14643	-0.08923	-0.05719
Tanytarsus mendax-type	Tmend	0.26586	0.00253	-0.26838
Corynoneura edwardsi-type	Cored	0.27611	-0.03498	-0.24113
Zavreliella	Zavrla	0.30095	0.01752	-0.31847
Psectrocladius limbatellus-type	Pslim	0.31852	-0.26168	-0.05684
Einfeldia pagana-type	Epag	0.39034	-2.13646	1.74612
Corynoneura coronata-type	Corco	0.39065	-0.18955	-0.20110
Parachironomus varus-type	Parva	0.43068	-0.50162	0.07094
Cladotanytarsus mancus-type	Cladm	0.49879	-0.40584	-0.09296
Psectrocladius barbatipes-type	Psbar	0.55727	-0.72713	0.16986
Psectrotanypus varius	Psvar	0.57131	-0.52320	-0.04811
Chaetocladius piger-type	Chpig	0.59377	-0.55607	-0.03770
Acricotopus	Acric	0.60384	-0.90189	0.29805
Tanytarsus lactescens-type	Tlact	0.60694	-0.62213	0.01519
Glyptotendipes caulicola-type	Glcau	0.66294	-1.67776	1.01482
Glyptotendipes barbipes-type	Glbar	0.68749	-0.78679	0.09930
Cricotopus tremulus-type	Crtre	0.71508	-0.83842	0.12333
Cricotopus obnixus-type	Crobn	0.73605	-0.68668	-0.04937
Phaenopsectra type A	PhA	0.74107	-1.35441	0.61333
Paratanytarsus type A	ParA	0.75473	-0.96099	0.20626
Psectrocladius flavus-type	Psfla	0.75913	-1.17413	0.41500
Paratendipes albimanus-type	Paral	0.76403	-0.92781	0.16378
Lauterborniella	Lauter	0.80870	-1.71810	0.90941
Pseudosmittia	Psmitt	0.82449	-0.97423	0.14974
Cryptochironomus	Crypch	0.86413	-1.09680	0.23266
Micropsectra pallidula-type	Mpall	0.87730	-1.16285	0.28555
Nanocladius rectinervis-type	Nanre	0.87730	-1.16285	0.28555
Paracricotopus	Paracr	0.87730	-1.16285	0.28555
Rheotanytarsus	Rheota	0.87730	-1.16285	0.28555
Diplocladius	Diploc	0.88132	-1.18650	0.30518

Kiefferulus tendipediformis	Ktend	0.88446	-1.48012	0.59566
Thienemannimyia group	Thiene	0.89574	-1.17207	0.27633
Paratanytarsus austriacus-type	Parau	0.89889	-1.46570	0.56681
Glyptotendipes severini-type	Glsev	0.91695	-1.28542	0.36847
Tanytarsus chinyensis-type	Tchin	0.91695	-1.28542	0.36847
Dasyhelea-type	CDasy	0.92774	-1.43684	0.50910
Natarsia	Natars	0.93137	-1.27099	0.33962
Pseudorthocladius	Psorth	0.93137	-1.27099	0.33962
Endochironomus albipennis-type	Endal	0.93665	-1.21416	0.27751
Smittia foliacea-type	Smitf	0.97078	-1.12848	0.15770
Einfeldia natchitocheae-type	Enat	0.97102	-1.39357	0.42255
Cladopelma viridulum-type	Clvir	0.98544	-1.37914	0.39369
Hydrobaenus conformis-type	Hydco	0.98544	-1.37914	0.39369
Micropsectra contracta-type	Mcont	0.98544	-1.37914	0.39369
Rheocricotopus fuscipes-type	Rheof	0.98544	-1.37914	0.39369
Stictochironomus rosenshoeldi-type	Stros	0.98544	-1.37914	0.39369
Tanytarsus glabrescens-type	Tglab	0.98544	-1.37914	0.39369
Tanytarsus lugens-type	Tluge	0.99624	-1.53056	0.53432
Corynoneura antennalis-type	Coran	1.00389	-1.38836	0.38447
Micropsectra insignilobus-type	Mins	1.01066	-1.51614	0.50547
Paracladopelma	Paracl	1.01066	-1.51614	0.50547
Polypedilum convictum-type	Pconv	1.01066	-1.51614	0.50547
Eukieferiella devonica-type	Eudev	1.02509	-1.50171	0.47662
Stenochironomus	Stenoc	1.02509	-1.50171	0.47662
Eukiefferiella	Eukief	1.03952	-1.48728	0.44777
Metriocnemus eurynotus-type	Meteu	1.03952	-1.48728	0.44777
Micropsectra junci-type	Mjunc	1.03952	-1.48728	0.44777
Stempellinella-Zavrelia	StZav	1.04078	-1.40681	0.36603
Einfeldia dissidens-type	Ediss	1.04353	-1.51093	0.46740
Anatopynia	Anatop	1.05796	-1.49651	0.43854
Cryptotendipes	Crypte	1.05796	-1.49651	0.43854
Metriocnemus terrester-type	Mette	1.05796	-1.49651	0.43854
Stempellina	Stempe	1.05796	-1.49651	0.43854

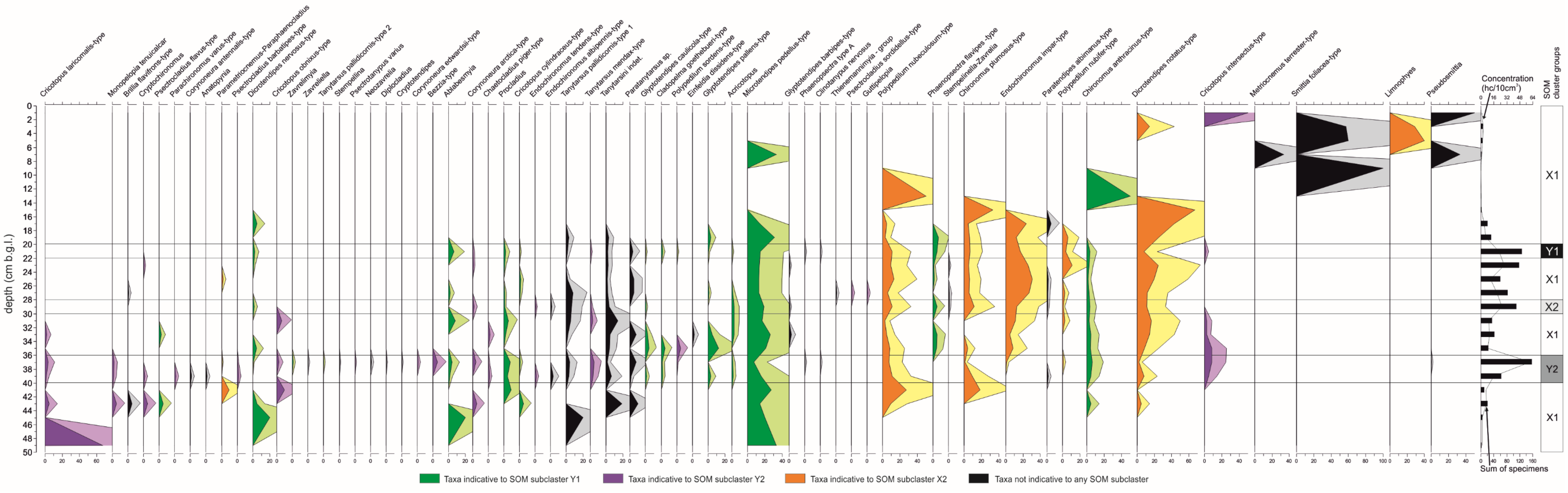
Clinotanypus nervosus	Clinn	1.06198	-1.52015	0.45818
Brillia flavifrons-type	Brilf	1.07640	-1.50573	0.42932
Neozavrelia	Neozav	1.07640	-1.50573	0.42932
Polypedilum nubifer-type	Pnubi	1.16578	-1.10704	-0.05874



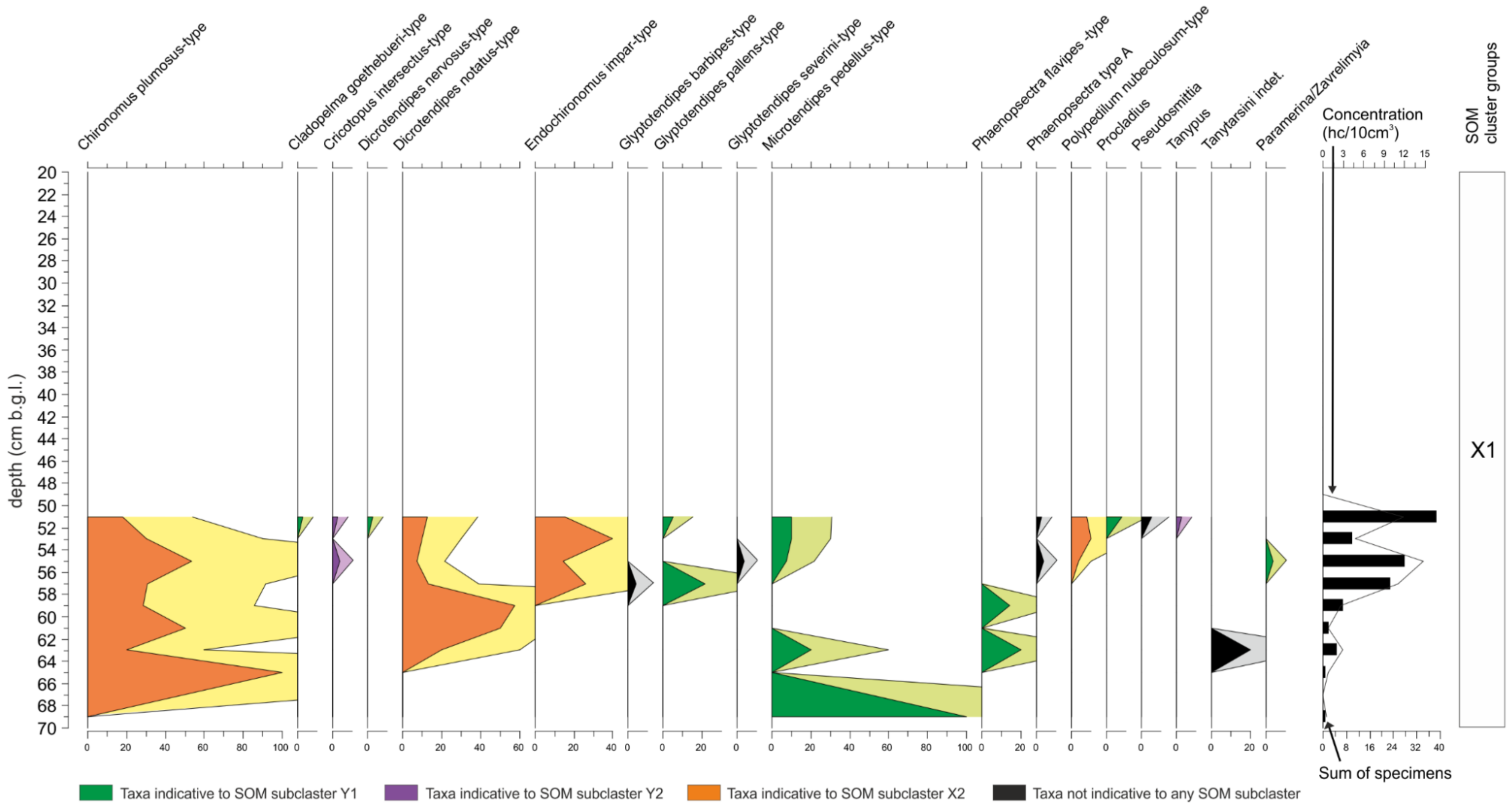
Supplementary Figure S1. Percentage Chironomidae stratigraphic diagram for the main moat fill from core RP W3 (2). The graphs of taxa indicative for each SOM subcluster (see Fig. 3) are coloured.



Supplementary Figure S2. Percentage Chironomidae stratigraphic diagram for the main moat fill from core RP W3 (4). The graphs of taxa indicative for each SOM subcluster (see Fig. 3) are coloured.



Supplementary Figure S3. Percentage Chironomidae stratigraphic diagram for the main moat fill from core RP W1. The graphs of taxa indicative for each SOM subcluster (see Fig. 3) are coloured.



Supplementary Figure S4. Percentage Chironomidae stratigraphic diagram for the secondary moat fill from core RP F2. The graphs of taxa indicative for each SOM subcluster (see Fig. 3) are coloured.

Chapter VI. Chironomidae morphological types and functional feeding groups as a habitat complexity vestige

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Chironomidae Morphological Types and Functional Feeding Groups as a Habitat Complexity Vestige

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Chironomidae Morphological Types
and Functional Feeding Groups as
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Chironomid (Diptera: Chironomidae) larvae play an important role in a wide range of aquatic ecosystems. The study focuses on Chironomidae trophic guilds and morphological types as indicator traits in reconstructions of habitat changes in shallow water bodies. Mentum and ventromental plates are important mouthparts whose shape depends on food type and feeding behavior. Chironomidae larvae strongly vary in the mode of life and feeding habits, representing almost every feeding group. Here we classified the mentum types into 16 groups and tested if they indicated similar past habitat changes as the Chironomidae functional feeding groups (FFGs), and tribes/subfamilies. Paleoecological data of biotic and abiotic proxies were derived from short sequences from a Late Glacial oxbow and a nearby medieval moat located in Central Poland. The study revealed that the habitat substratum structure, vegetation and physicochemical conditions are associated both with the feeding types and morphological traits. This provides a valuable tool for future reconstructions of habitat changes.

Keywords: Diptera, functional feeding groups, trophic guilds, paleoecology, paleolimnology, habitat reconstruction, environmental changes, mouthpart morphology

INTRODUCTION

Chironomidae are one of the most abundant and ubiquitous groups of aquatic insects. Their sensitivity to changing limnological conditions and species-specific environmental preferences make them good ecological indicators (Armitage et al., 1995; Porinchu and MacDonald, 2003). A variety of environmental variables affects Chironomidae larvae both in a direct and indirect way. Among local-scale abiotic factors, some of the most important for chironomids are pH, lake depth and water nutrient status (Walker, 2001; Brooks et al., 2007; Płóciennik et al., 2020). As there are some truly rheophile taxa, chironomid subfossils can indicate a connection of peripheral river valley water bodies to the main stream during overbank episodes (Gandouin et al., 2006;

Howard et al., 2010; Kittel et al., 2016). They also indicate a stagnant water level in a quantitative way (Luoto, 2009a). While a relation of littoral versus profundal taxa reflects lake-level changes, semi-terrestrial taxa indicate paludification and terrestrialisation processes (Frouz, 1999; Brooks et al., 2007; Lamentowicz et al., 2009). When pH drops below 6.0, chironomid assemblages are mostly replaced by Chaoboridae or Ceratopogonidae (Henrikson et al., 1982; Walker et al., 1985). Even though most chironomid larvae prefer circum-neutral pH, certain taxa are characteristic to acidic or slightly alkaline conditions (Walker, 2001; Brooks et al., 2007). Generally, water pH exceeding 7.5 eliminates many taxa, reducing species richness. It is associated with increased eutrophication and oxygen deficiencies (Brooks et al., 2007). The extraordinarily wide spectrum of preferred water trophic states makes chironomids good indicators of lake nutrient status (Saether, 1979; Walker, 2001; Porinchu and MacDonald, 2003).

Chironomidae are applied in inference models developed as a tool for many quantitative climatic and environmental reconstructions (e.g., Brooks et al., 2001; Luoto, 2009b; Heiri et al., 2011; Kotrys et al., 2020). However, the use of chironomid autecology for reconstruction of aquatic habitats is a time-consuming method and requires high competition in subfossil identification. The acquisition of necessary experience for chironomid identification takes years of work and there are still too few specialists to meet the needs of European paleoecological projects. But, while standard analysis is impossible, the functional trait approach may be applied. This method allows for tracking past shifts in the functional groups of organisms, and thus studying the long-term ecosystem response to past environmental changes (Gregory-Eaves and Beisner, 2011). So far, functional traits of several groups of organisms have been studied according to their application in paleoecology (e.g., Vogt et al., 2010; Fournier et al., 2015; Nevalainen and Luoto, 2017). The functional traits carried by chironomid larvae have so far been studied mainly by Serra et al. (2016, 2017). Here we want to verify the applicability of this method in Chironomidae subfossil analysis.

Functional traits are the features of organisms indicating environmental changes (response traits) or driving such changes in the ecosystems (effect traits) (Nock et al., 2016). They are widely used in community ecology, studying the ecological niche (Kearney et al., 2010), improving ecological process analyses and quantifying the influence of assemblage shifts (Díaz and Cabido, 2001; Nock et al., 2016). Community-trait approach, which takes into considering community weighted means of traits (CWMs), is a noteworthy method (Garnier et al., 2007; Kleyer et al., 2012). Several indices were constructed for functional diversity calculation (reviewed in Pla et al., 2012), providing a broader view for ecosystem complexity than species richness (e.g., Stuart-Smith et al., 2013). The Chironomidae taxonomic and functional diversity across various environmental gradients have been already studied in several regions of the world (e.g., Milošević et al., 2018; Jiang et al., 2019; Motta and Massaferro, 2019; Ni et al., 2020), while Nevalainen et al. (2015) focused on the results provided by the subfossil chironomid assemblages. Kivilä et al. (2019, 2020) used chironomid functional feeding groups (FFGs) to track not only recent habitat changes, but also climate warming in northern Finland. However, food preferences of some taxa are still not well-specified. To avoid loss of data, morphological traits such as the mouthpart structure may serve as a good surrogate. Several studies have proven that morphological features of some organisms, such as testate amoebae (e.g., Fournier et al., 2015; Lamentowicz et al., 2015), cladocerans (Nevalainen and Luoto, 2017) and plants (e.g., Woodward, 1987; Reitalu et al., 2015; Carvalho et al., 2019) can be used to infer past environmental changes, both on a micro- and macroscale. The study by Barboni et al. (2004) indicates that plant response to climate changes (reflected in pollen analysis) is more diagnostic in combinations of traits rather than in individual traits. This assumption is likely applicable to every biological proxy, including chironomids. Consequently, future studies on shifts in habitat structure should apply appropriate methods that take into consideration the complexity of aquatic ecosystems.

Trait-based studies help researchers understand the mechanisms of ecological processes and, therefore, their potential in paleoenvironmental reconstructions cannot be ignored (Marcisz et al., 2020). The studied organisms were affected over time by a range of direct and indirect variables. One of such indirect factors was human activity, which impacted aquatic habitats in many ways. Therefore, the study includes both truly natural and artificial water bodies. The results of the previous study concerning the moat system of the motte-and-bailey stronghold in Rozprza (Kittel et al., 2018a) were utilized. In its case, human impact turned out to be one of the main factors. The inhabitants caused the increase of water trophy, but also changed water dynamics by creating artificial channels (Kittel et al., 2018a). In order to check the applicability of the proposed method in a natural ecosystem, the results of paleoecological studies of the nearby paleo-oxbow were also included.

Morphological characters and well-established ecological preferences are key traits in paleolimnology (Gregory-Eaves and Beisner, 2011). The study focuses on the morphological traits (mouthparts type) which are thought to be (at least partially) dependent on feeding preferences, and thus also associated with the habitat character. The habitat structure is expressed not only by physicochemical features but also by biological variables, such as macrophytes and diatoms, included in our study. Langdon et al. (2010) state that biotic variables are even more important than the abiotic ones in determining zoobenthos communities in temperate shallow lakes, and chironomids are very good indicators of past changes in the primary production, as well as macrophyte abundance and structure. Our primary goal is to recognize if the traits carried by the Chironomidae at different organization levels indicate similar habitat changes in the context of paleoenvironmental reconstructions.

Chironomidae vary not only in their environmental preferences but also in their diet type. Although the larval feeding behavior depends on many factors, such as larval size, food quality, and availability (Berg, 1995), each species seems to have specific preferences, often associated with its habitat type. Representatives of almost every feeding group can be found among chironomids. There are sediment collectors such as *Chironomus plumosus*-type, phytophagous shredders such as *Glyptotendipes caulicola*-type, and scrapers (many Orthocladiinae). Such a great variety is associated with their diverse modes of life – some of them live in tubes built out of sediment (e.g., *Chironomus* and Tanytarsini), while others are free-living and predatory, such as Tanypodinae. Chironomids include detritus feeders, parasites, commensals, and plant miners (Berg, 1995; Walker, 2001; Beiger, 2004; Vallenduuk and Moller Pillot, 2007; Moller Pillot, 2009, 2013; Schiffels, 2014).

Larvae morphology, especially their mouthparts, had to be adapted to their diet and feeding behavior. The relationship between mandibles and chironomid autecology was studied using the geometric morphometrics approach (Đurđević et al., 2017). Mandibles and labrum are important features, useful in diagnostics, but they are often missing from the subfossil material. Other mouthparts, likely related to the diet, are mentum and ventromental plates. This is the reason for choosing them as the key characteristics for morphological types in our study. The shape of the mentum may be similar even between taxonomically distant taxa. For example, the concave mentum of predatory *Cryptochironomus* resembles the dorsomentum of many Tanypodinae (e.g., *Procladius*), while striated plates are often characteristic of filtrating Chironominae (Olafsson, 1992; Moller Pillot, 2009).

Considering this, we can assume that some generalization in the morpho-functional traits of Chironomidae can be done. However, we need to be careful with some morphologically close species which vary in their feeding behavior (Monakov, 1972). In paleoecological studies, chironomids are mostly identified to the morphotype level, which usually includes closely related species with similar ecology. On the other hand, it is sometimes impossible to distinguish subfossil head capsules of ecologically different taxa, such as *Micropsectra insignilobus* and *M. atrofasciata, Chironomus tenuistylus* and *Ch. plumosus,* or *Stempelinella* and *Zavrelia* (Brooks et al., 2007). Nevertheless, chironomid mouthparts are closely related to their feeding type, which often reflects the habitat structure. It raises the question if the knowledge of certain species' autecology is always required for reconstructions of environmental conditions? Perhaps some general assessments can be done, even by non-specialists, on the basis of mentum shape. In this case, such preliminary chironomid analyses based on the proposed mentum classification could bring valuable insight into past ecosystems, even when undertaken during a macrofossil analysis.

Mentum and ventromental plates are also the main differing features between subfamilies and tribes. Although there are eleven Chironomidae subfamilies, three of them are the most species-rich: Chironominae, Orthocladiinae, and Tanypodinae (Brooks et al., 2007; Ferrington, 2008). In this study, we focus on these subfamilies, as their representatives were found in examined sediments. Chironominae are usually characterized by distinctive, striated, large ventromental plates and a slightly convex mentum. The mentum of Orthocladiinae is often strongly convex, their head capsules are usually smaller, and ventromental plates are mostly inconspicuous. Tanypodinae have a toothed ligula, a less developed mentum, and no ventromental plates. Some chironomid subfamilies are divided into tribes. In the studied sequences, taxa belonging to Macropelopiini, Natarsiini, Pentaneurini, Procladiini, Tanypodini (Tanypodinae), as well as to Chironomini and Tanytarsini (Chironominae), and to Orthocladiinae were recorded. Among Tanypodinae, only Macropelopiini, Procladiini and Tanypodini have dorsomental teeth. Natarsiini and Pentaneurini are characterized by a bright, elongated head and a membranous toothless mentum that is not well-preserved in subfossil material. Chironomini have relatively large, fan-shaped ventromental plates, while the plates of Tanytarsini are usually bar-shaped and straight (Brooks et al., 2007; Andersen et al., 2013). The Orthocladiinae are rarely divided into tribes (Spies, 2005), so we left this group undivided at the subfamily level.

Finally, the goal of this study is to check whether (and how) some chironomid groups (mentum types, trophic guilds, or tribes/subfamilies) are correlated with other indicators within studied proxies (macrophytes and other plants, diatoms, sediment type or geochemical components). The applicability of morphological functional traits in paleoecological research was verified. Presumably, they could serve as surrogate indicators where it could be applicable.

STUDY AREA

The study area (51°18′07″ N; 19°40′04″ E; 182–183 m a.s.l.) is situated in Central Poland, approx. 60 km south of Łódź. It is located in the valley floor of the Luciąża River, a 3rd-order river in the Vistula River basin.

The region is a part of the Odranian (Saalian) formerly glaciated area – the last ice sheet was present here in the Wartanian Cold Stage of the Odranian Glaciation (Marks, 2011). Intense transformation of river valleys took place during the Weichselian glacial period under periglacial conditions. While the valley floor is strongly expanding in the Rozprza area, residual terraces occur within the Holocene floodplain (Goździk, 1982; Kittel et al., 2018b).

In the opinion of Wachecka-Kotkowska (2004a,b), the morphology of the Luciąża valley floor was obliterated by the deposition of modern overbank alluvium. However, this landscape reconstruction has not been confirmed by a detailed examination of surficial geology in the Rozprza area (Kittel et al., 2018a,b). In the recent research, numerous subfossil paleomeanders of different sizes have been discovered in the valley floor (**Figure 1**). A large paleochannel (W4) was recorded as a strong curvilinear magnetic anomaly with a width of ca. 10 m, and a radius of ca. 15 m. It is filled with organic mud and coarse-detritus gyttja reaching 1.3 m thickness and underlain by channel alluvia of sands and gravels with organic admixtures and laminations of organic mud. Radiocarbon data evidences the channel's cut-off in the Late Allerød. The paleochannel fill is overlain by the overbank alluvia of sandy organic mud (Kittel et al., 2018b).

The Rozprza motte-and-bailey moat system was established in the 1330s AD and is now filled with organic (gyttja and peat) and partially inorganic deposits containing rich remains of wood. The medieval age of the features has been confirmed by dendrochronological and radiocarbon AMS date sets. The fill of

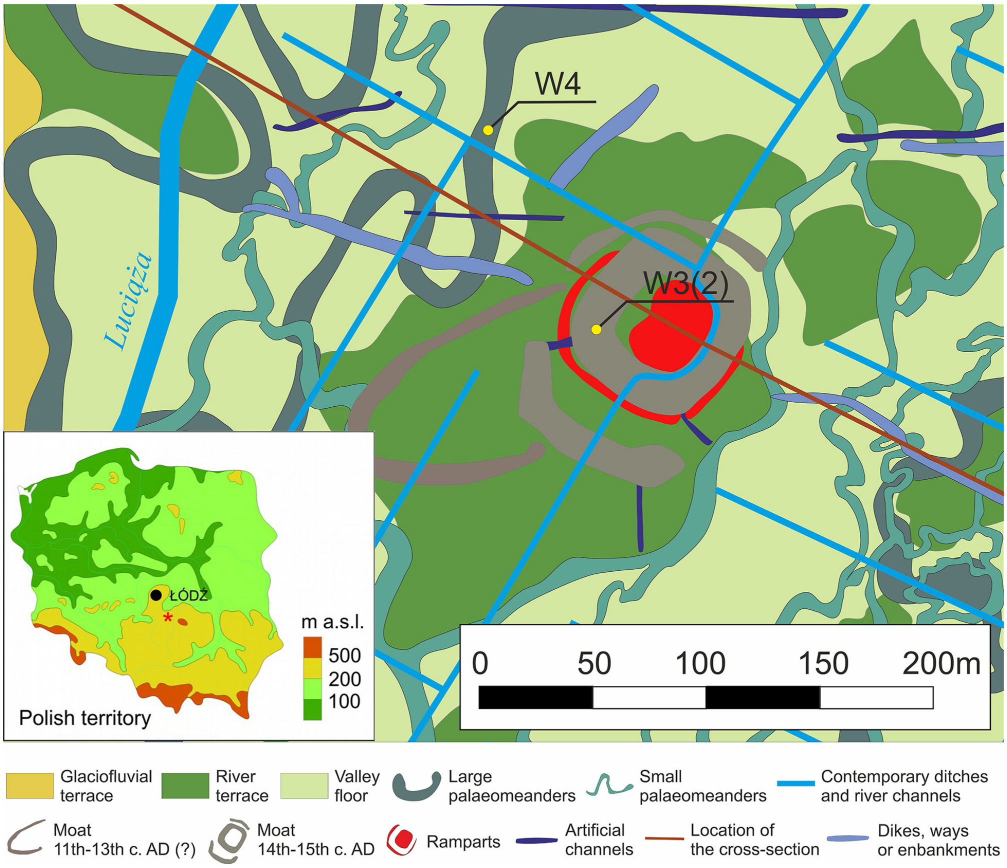


FIGURE 1 | The geomorphological map of the vicinity of Rozprza archaeological site with the location of W4 (paleo-oxbow) and W3(2) (moat) profiles (marked as yellow dots) (after Kittel et al., 2015, 2018b, modified). In the map of Poland, Rozprza is marked with an asterisk.

the main moat was a subject of a detailed paleoenvironmental study (Kittel et al., 2018a). The accumulation of overbank silty sandy organic mud took place within the moat ditch system as late as in the 18th or 19th c. CE (Kittel et al., 2018a,b).

The potential natural vegetation of the Luciąża River valley would have been mostly lime-oak-hornbeam forests representing the *Tilio-Carpinetum* association and, to a lesser extent, the *Potentillo albae-Quercetum* typicum. Immediate surroundings of the water courses would have been overgrown by lowland ash-alder and alder forests of *Fraxino-Alnetum* and *Carici elongatae-Alnetum* associations (Matuszkiewicz, 2008).

The sediment cores were taken from the same area, but they are dated to different time periods. The W3(2) sequence originates from the Late Medieval moat, while the W4 core covers the Late Weichselian paleochannel history (**Figure 1**).

MATERIALS AND METHODS

Fieldwork and Geochronology

The fieldwork in Rozprza was conducted in 2015–2016, as part of a multidisciplinary archaeological investigation of the medieval ringfort remnants. In order to choose proper sampling sites in the field, not only was topography and geomorphology of studied area thoroughly mapped but also the combination of other non-destructive methods (including aerial photography, geophysical, and geochemical survey) was used (Sikora et al., 2015, 2019; Kittel et al., 2018b).

The sediments for paleoecological analyses were collected from the trench walls as monoliths using metal boxes (50 × 10 × 10 cm each). With this method, the undisturbed structure of the sediments was preserved. Five selected samples of bulk organic deposits collected from the W3(2) profile and two bulk samples from the W4 profile were dated with the radiocarbon (^{14}C) method, using the liquid scintillation technique (LST). Two samples of selected terrestrial plant macrofossils from the W3(2) core and three samples from the W4 core were dated using accelerator mass spectrometry technique (AMS). Moreover, a dendrochronological analysis was performed to determine the age of the moat fill (Kittel et al., 2018a).

Geochemical and Sedimentological Analyses

For geochemical analyses, samples from both cores were dried at 105°C and homogenized. The organic matter content was obtained using the loss on ignition (Heiri et al., 2001).

Carbonate content was determined using the volumetric method with Scheibler's apparatus, and pH by a mean potentiometric method in distilled water. The ash samples were dissolved (with HCl, HNO_3, and H_2O_2) in Teflon bombs using a microwave mineralizer. For the solution analyzed concentrations of such elements as: Na, K, Mg, Ca, Fe, Mn, Cu, Zn, and Pb, the atomic absorption spectrometry (AAS) was used. Grain size composition of the ash samples, remaining after the solution was made in accordance with Clift et al. (2019), was determined using a Mastersizer 3000 laser particle-size analyzer (Malvern). The relationship between the mean grain size and the sorting index (the so-called coordinate system) follows Mycielska-Dowgiałło and Ludwikowska-Kêdzia (2011).

Biotic Proxies

Chironomidae sample processing followed the methods outlined in Brooks et al. (2007). The sediment volume ranged between 1 and 10.5 cm^3 per sample. The sediments were passed through a 63 μm mesh sieve. If necessary, kerosene flotation was used according to the method of Rolland and Larocque (2007). Processed sediment was put into a Bogorov counting tray and scanned under a stereo-binocular microscope. Where applicable, at least 50 (preferably 100) chironomid head capsules from each sample were picked and mounted in Euparal® on microscope slides. Identification of chironomid head capsules followed keys by Schmid (1993), Brooks et al. (2007), and Andersen et al. (2013). Chironomidae taxa were classified in three ways: taxonomically (subfamilies and tribes), morphologically and by feeding group. Sixteen morphological types were distinguished based on the larvae mouthpart structure, namely: the mentum ratio (width/height), the median and lateral mentum teeth structure, as well as the size and shape of ventromental plates (**Figure 2**). Most types were distinguished within Chironomini and Orthocladiinae. Tanypodinae with toothed dorsomentum were grouped together with *Cryptochironomus*, while for Pentaneurini and *Natarsia* (with toothless mentum) a separate group was created. Tanytarsini were classified into two types, depending on the shape and length of ventromental plates (**Table 1**). The recorded taxa were also divided into 12 functional feeding groups (FFGs): collector-gatherers (C), collector-filterers (C/F), collectors/grazers (C/G), shredders/filterers (S/F), shredders/collectors (S/C), grazers/scrapers (G), grazers/collectors (G/C), filterers/collectors (F/C), filterers/grazers (F/G), miners (M), predators (P), and predators/collectors (P/C). The feeding preferences of identified taxa are based mainly on Franquet (1999), Vallenduuk and Moller Pillot (2007), Moller Pillot (2009, 2013), and Serra et al. (2016). The stratigraphic diagrams were created with C2 software (Juggins, 2007).

Samples for a plant macrofossil analysis were wet-sieved in a 200 μm mesh, then boiled with KOH to reduce the amount of sediment and remove humic matter. The material was examined under a microscope. Conservation of plant remains was done with a standard mixture of alcohol, water and glycerine, with addition of thymol. Fragments of plants were then dehydrated in 50% ethyl alcohol. Macrofossils were identified using plant keys, atlases (e.g., Greguss, 1945; Kats et al., 1965; Grosser, 1977; Schweingruber, 1978; Berggren, 1981; Cappers et al., 2006; Velichkevich and Zastawniak, 2006, 2008; Schweingruber et al., 2011), scientific descriptions and publications, a reference collection of modern seeds, fruits, wood and charcoal, and a collection of fossil floras of the W. Szafer Institute of Botany, Polish Academy of Sciences, in Kraków.

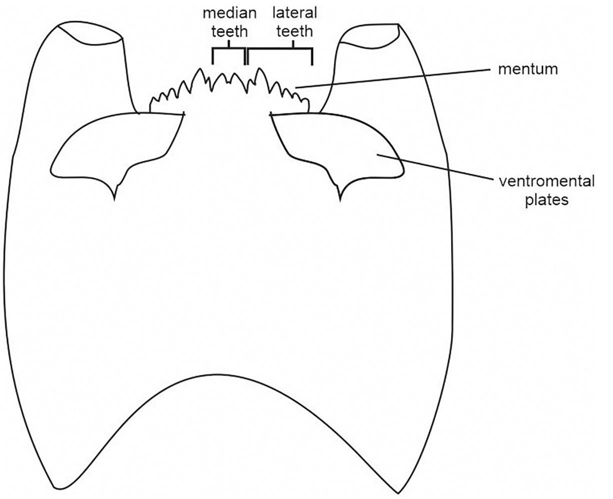


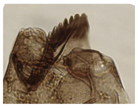
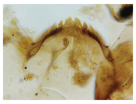
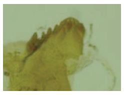
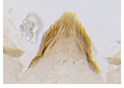
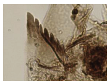
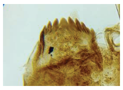
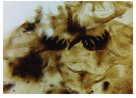
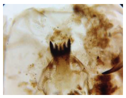
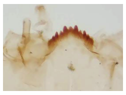
FIGURE 2 | Chironomidae head capsule with mouthpart structure.

A diatom analysis was conducted according to the method by Battarbee (1986). Samples of 1 cm^3 each from the cores were processed. Sediments were treated in 10% HCl to remove calcium carbonate and washed several times in distilled water. Afterward, the samples were boiled in 30% H_2O_2 to digest the organic matter. Finally, the samples were washed several times in distilled water. Microspheres were added to each sample in order to determine the frequency of the diatoms in each sample (Battarbee and Kneen, 1982).

Statistical Analyses

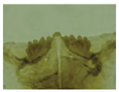
All statistical analyses were made in R software (R Core Team, 2020). Firstly, environmental data were standardized using the robustHD package (Alfons, 2019). The corrplot package (Wei and Simko, 2017) was used to compute Pearson's correlation matrix in order to check which environmental variables were correlated (correlation >0.70) with each other (**Supplementary Figures 1**, **2**). The most autocorrelated predictors were removed from the analysis. Finally, eight variables: pH, $CaCO_3$, organic matter (OM), K, sand, wood, Carex sp., and U. dioica were included in further analysis (**Supplementary Table 1**). Next, a dataset for each group of Chironomidae was square-root transformed, in order to reduce the influence of outliers. The "decorana" function from the vegan package (Oksanen et al., 2019) was used to fit the best ordination analysis to the datasets of each group. A Redundancy Analysis (RDA) was performed for each Chironomidae typology using the vegan package (Oksanen et al., 2019). To determine collinearity between environmental factors shaping chironomid composition, variance inflation factors (VIF) analysis was used

TABLE 1 | Chironomidae morphological types.

Morphological type	Description	Morphospecies from this study	Example
1	- One broad or several smaller median teeth - Narrow plates with setae - Mentum ratio > 3	*Acricotopus, Diplocladius, Psectrocladius barbatipes*-type, *P. flavus*-type	 *Diplocladius*
2	- Two median teeth - Broadening/narrow ventromental plates - Mentum ratio 2.2–2.9	*Chaetocladius piger*-type, *Metriocnemus fuscipes*-type, *Heterotrissocladius marcidus*-type, *H. grimshawi*-type, *Hydrobaenus conformis*-type, *Nanocladius rectinervis*-type, *Psectrocladius sordidellus*-type, *P. limbatellus*-type	 *Chaetocladius piger*-type
3	- Large, fan-shaped plates - One/trifid median tooth - Mentum ratio 2.9–3.9	*Glyptotendipes barbipes*-type, *G. pallens*-type, *Chironomus plumosus*-type, *Ch. anthracinus*-type	 *Chironomus anthracinus*-type
4	- Fan-shaped plates - Cluster of outermost lateral teeth	*Cladopelma viridulum*-type, *Cladopelma goetghebueri*-type	 *Cladopelma viridulum*-type
5	- Tanytarsini - Long ventromental plates, close together	*Micropsectra contracta*-type, *M. insignilobus*-type, *M. pallidula*-type, *Tanytarsus chinyensis*-type, *T. lactescens*-type, *T. lugens*-type, *T. mendax*-type, *T. nemorosus*-type, *T. pallidicornis*-type, *Paratanytarsus austriacus*-type, *P. penicillatus*-type, *P.* type A, *Rheotanytarsus*	 *Micropsectra contracta*-type
6	- Broadening/narrow ventromental plates - Mentum ratio < 2.2	*Corynoneura arctica*-type, *C. coronata*-type, *C. edwardsi*-type, *Rheocricotopus effusus*-type, *Eukieferiella coerulescens*-type	 *Corynoneura arctica*-type
7	- One broad median tooth - Narrow ventromental plates - Mentum ratio ca. 2	*Cricotopus bicinctus*-type, *C. cylindraceus*-type	 *Cricotopus cylindraceus*-type
8	- One median tooth - narrow ventromental plates - Mentum ratio 2–2.9	*Cricotopus intersectus*-type, *C. laricomalis*-type, *Orthocladius trigonolabis*-type, *O.* type S, *O.* type I, *Metriocnemus terrester*-type	 *Metriocnemus terrester*-type
9	- Concave mentum	*Cryptochironomus, Procladius, Tanypus, Psectrotanypus, Derotanypus*	 *Cryptochironomus*
10	- Fan-shaped plates - Mentum ratio 2–2.5	*Dicrotendipes nervosus*-type, *D. notatus*-type, *Glyptotendipes caulicola*-type, *G. severini*-type	 *Glyptotendipes severini*-type
11	- No teeth on mentum	*Natarsia, Ablabesmyia, Clinotanypus nervosus, Guttipelopia, Larsia, Krenopelopia, Monopelopia, Paramerina, Thienemannimyia group, Zavrelimyia*	 *Ablabesmyia*
12	- Fan-shaped plates - 3–4 median teeth higher than lateral ones - Mentum ratio 2.9–4.1	*Endochironomus tendens*-type, *E. impar*-type, *E. albipennis*-type, *Phaenopsectra* type A, *P. flavipes*-type, *Stictochironomus roesenschoeldi*-type, *Sergentia coracina*-type, *Polypedilum sordens*-type	 *Endochironomus tendens*-type

(Continued)

TABLE 1 | Continued

Morphological type	Description	Morphospecies from this study	Example
13	- Fan-shaped plates - 3–4 median teeth brighter than lateral ones - Mentum ratio 3.2–3.7	*Microtendipes pedellus*-type, *Paratendipes albipennis*-type, *P. nudisquama*-type	 *Microtendipes pedellus*-type
14	- Large fan-shaped plates - 2 median teeth - First lateral tooth lower	*Polypedilum nubeculosum*-type, *P. nubifer*-type, *Lauterborniella, Zavreliella*	 *Polypedilum nubeculosum*-type
15	- Ventromental plates narrow or foot-shaped - One broad median tooth or two median teeth - 4–5 lateral teeth - Mentum ratio ca. 3	*Metriocnemus eurynotus*-type, *Parametriocnemus-Paraphaenocladius, Smittia foliacea*-type, *Pseudosmittia, Pseudorthocladius, Limnophyes, Paralimnophyes*	 *Metriocnemus eurynotus*-type
16	- Tanytarsini - Broad, well separated ventromental plates	*Constempellina-Thienemanniola, Stempelinella-Zavrelia*	 *Constempellina -Thienemanniola*

(Fox and Weisberg, 2011). In addition, ANOVA was conducted to determine statistically significant variables (Oksanen et al., 2019). These variables were used in subsequent RDA analysis. Adjusted R^2 indicated how much variability was explained by the RDA analysis. Eigenvalues of RDA axes (RDA1 and RDA2) were computed to compare the proportions of variance explained between each analyzed group of chironomids. Eight environmental factors (pH, $CaCO_3$, organic matter, K, sand, wood, Carex sp., and U. dioica) were used in generalized linear models (GLMs) as fixed effects to assess their influence on the richness of chironomid tribes/subfamilies, mentum types and feeding types. Models were selected using the "dredge" function from the MuMIn package (Bartoń, 2018). Next, the most parsimonious models (with $\Delta AIC < 2$) were averaged into one model to determine statistically significant environmental variables. In addition, the hier.part package (Walsh and Mac Nally, 2013) was used to calculate the independent effects of each variable on the richness as well as its significance. Charts were created using the ggplot2 package (Wickham, 2016).

RESULTS

Chironomidae Stratigraphy

From a short, Late Weichselian paleochannel sequence (W4), 1138 chironomid head capsules were collected and identified to 56 morphospecies. The chironomid fauna in the paleochannel underwent significant fluctuations. After the favorable conditions for chironomid assemblages in the Allerød and Younger Dryas, their number suddenly dropped in the Holocene. Because of a very low chironomid concentration in that period (<50 head capsules), further analyses were based only on the Late Weichselian part of the sequence (ca. 13,000 – 12,200 cal. BP). During this whole period, collectors, represented mainly by Tanytarsini with mentum type 5, clearly dominated. Their relative proportion ranged between 15 and 60%, with the peak in the Late Allerød (194–198 cm b.g.l.). This was the time when the share of subdominant grazers (G, G/C) dropped. Interestingly, in the Younger Dryas (180–190 cm b.g.l.), the share of collectors (here mentum type 5, predominantly *Micropsectra*) slightly decreased, which coincides with the increase in the proportion of larvae with mentum type 1 (mainly *Acricotopus*). Besides that, the share of semiterrestrial taxa (grazers/collectors, mostly *Limnophyes-Paralimnophyes* and *Parametriocmenus-Paraphaenocladius*) was significant (**Figure 3**).

In the Late Holocene moat sequence [W3(2)], as many as 2488 head capsules of 83 Chironomidae morphospecies were recorded. The sequence reveals clear shifts in chironomid composition. The first phase is characterized by high complexity of chironomid assemblages. Worth noting is a particularly high share of predatory taxa (mainly Tanypodinae), shredders/collectors (mainly *Psectrocladius*) and grazers (mainly *Corynoneura*), but also many other groups, including grazers/collectors represented here by *Cricotopus*. When the abundance of chironomid larvae decreased in the 2nd half of the 16th century AD, semiterrestrial grazers/collectors started to dominate, accompanied by shredders/filterers (*Polypedilum nubifer*-type and *P. nubeculosum*-type). In the last phase, very few Chironomidae were found: firstly grazers/collectors, later mainly collectors (mentum type 10), collector/filterers and filterer/grazers (both representing mentum type 3) (**Figure 3**). For detailed reconstruction of the moat development, see Kittel et al. (2018a).

Tribes/Subfamilies

The ANOVA analysis for tribes/subfamilies showed that pH, K and organic matter played a significant role in shaping Chironomidae assemblages within analyzed cores (**Table 2**). The RDA plot (**Figure 4A**) revealed that W4 samples were associated

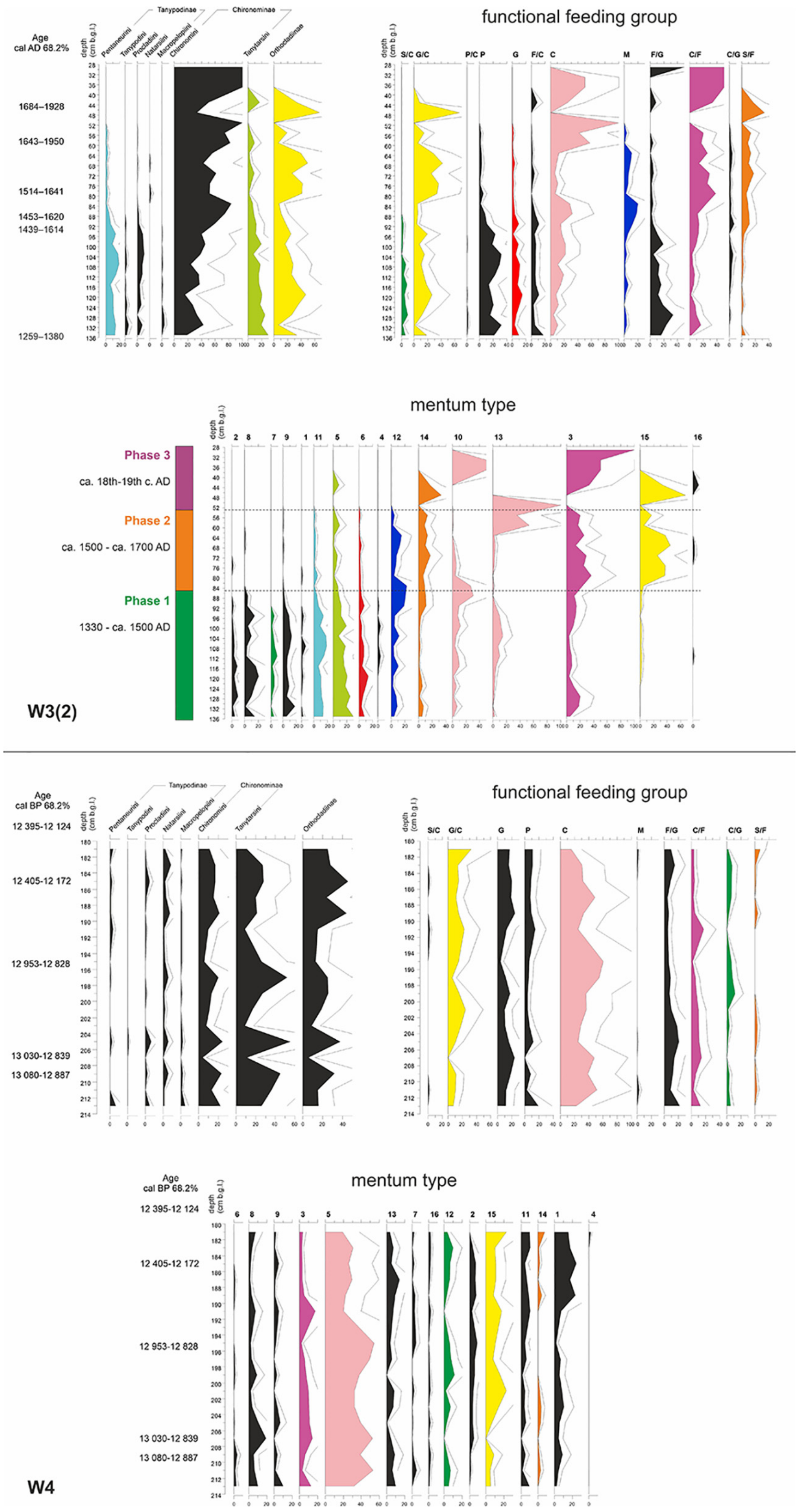


FIGURE 3 | Chironomidae stratigraphic diagrams of the W3(2) (top) and W4 (bottom) cores, according to three typologies: subfamily/tribe, functional feeding groups and mentum types. Similar trends in some groups are outlined by the same graph color. The bar alongside W3(2) diagram represents three phases of the moat development based on Chironomidae assemblages (Kittel et al., 2018a). The abbreviations used for functional feeding groups were as follows: C, collector-gatherers; C/F, collector-filterers; C/G, collectors/grazers; S/F, shredders/filterers; S/C, shredders/collectors; G, grazers/scrapers; G/C, grazers/collectors; F/C, filterers/collectors; F/G, filterers/grazers; M, miners; P, predators; and P/C, predators/collectors. The symbols used for morphological types are explained in **Table 1**.

TABLE 2 | Variance influence factors (VIFs) and significance of eight environmental factors selected from correlation matrices.

	Variable	VIF	Significance
Tribes/subfamilies	**pH**	**2.323**	**0.001**
	$CaCO_3$	1.267	0.092
	OM	**4.247**	**0.043**
	K	**2.925**	**0.002**
	Sand	2.635	0.418
	U. dioica	2.211	0.563
	Carex sp.	1.969	0.579
	Wood	2.098	0.064
Mentum type	**pH**	**2.324**	**0.001**
	$CaCO_3$	**1.267**	**0.033**
	OM	**4.247**	**0.003**
	K	**2.925**	**0.001**
	Sand	2.635	0.277
	U. dioica	2.211	0.662
	Carex sp.	1.969	0.326
	Wood	**2.098**	**0.028**
Feeding type	**pH**	**2.324**	**0.001**
	$CaCO_3$	1.267	0.275
	OM	**4.247**	**0.001**
	K	**2.925**	**0.001**
	Sand	2.635	0.864
	U. dioica	2.211	0.120
	Carex sp.	1.969	0.283
	Wood	**2.098**	**0.001**

Bolded variables were used in redundancy analysis.

with relatively low content of organic matter and K. Those two factors were correlated with the RDA2 axis. The samples from W3(2) core representing phases of moat development were clearly separated in the plot. The first phase was influenced by high pH and K values, as well as by abundance of Procladiini and Pentaneurini. Samples from the second phase were characterized by a dominance of Chironomini and high content of organic matter. The third phase, in turn, was characterized by low pH. The RDA explained 38% of variance from the analysis. While the RDA2 axis explained 11% of variance, the RDA1 axis described 31% of total variance. GLMs for Chironomidae tribes/subfamilies were initially calculated for eight predictors. Seven of them (pH, OM, $CaCO_3$, K, sand, wood, and *Urtica dioica*) were included in the averaged model. Among them, only pH was statistically significant and positively correlated with richness (**Figure 5A**). On the other hand, hierarchical partitioning (HP) revealed that both pH (independent effects: 70%) and *Urtica dioica* (independent effects: 14%) were statistically significant and had positive impact on tribes/subfamilies richness (**Figure 6A**).

Mentum Types

Five environmental factors: pH, organic matter, $CaCO_3$, K, and wood macrofossils were statistically significant in the ANOVA analysis for mentum types (**Table 2**). The RDA analysis showed that samples from different cores and phases were clearly distinguished. Chironomids with mentum types 1 and 5 were the most abundant in the W4 core, which may be associated with low content of wood, organic matter and potassium (factors correlated with the RDA2 axis). On the other hand, high pH (correlated with the RDA1 axis) and K values impacted the higher abundance of chironomids with 7, 8, 9, and 11 mentum types in the first phase of W3(2) core. The second phase was shaped by high content of wood, organic matter and low content of $CaCO_3$. Low pH values characterized phase 3 of the W3(2) core. The first two RDA axes explained 21% (RDA1) and 14% (RDA2) of variance, but with Adjusted R^2, the whole RDA analysis described 34% of variance. Six out of eight predictors: pH, $CaCO_3$, organic matter, K, sand, and wood macrofossils were included in the GLMs for richness of Chironomidae mentum types. However, only pH, organic matter and potassium were statistically significant and positively correlated with richness (**Figure 5B**). Hierarchical partitioning results for mentum types were similar to those for tribes/subfamilies. They revealed that both pH and *Urtica dioica* were significant and had positive correlation with independent effects reaching 64% and 16%, respectively (**Figure 6B**).

Feeding Groups

The ANOVA analysis revealed that four factors: pH, OM, K, and wood were significant for the composition of chironomid feeding groups (**Table 2**). RDA analysis supported the results for other chironomid typologies, where samples representing each core and phase created clear aggregations (**Figure 4C**). W4 samples were characterized by a low content of organic matter, wood and K (factors correlated with the RDA2 axis), as well as high abundance of collectors (C). Samples from the W3(2) core were distributed along the RDA1 axis. The first-phase samples were under the influence of pH (correlated with the RDA1 axis), with high abundance of S/C, P, and F/C feeding types. High content of organic matter and wood affected the aquatic organisms in the second phase, which might be reflected in the abundance of shredders/filterers (S/F). Phase 3 assemblages were shaped by low pH. The coefficient of determination (Adj R^2) for this dataset is 0.36. The RDA axis 1 described 26% of variance, while the second axis explained only 8%. Generalized Linear Models for feeding type richness included seven predictors: pH, organic matter, K, sand, *Urtica dioica*, *Carex* sp., and wood. However, only pH, organic matter and wood were statistically significant and showed positive correlation with richness (**Figure 5C**). Moreover, hierarchical partitioning indicated pH, OM, *Urtica dioica*, and wood (independent effect: 59, 11, 18, and 12%, respectively) as significant for shaping chironomid feeding types. All these factors were positively correlated with richness of feeding groups (**Figure 6C**).

The VIF values of all environmental variables in each RDA analysis were <10.0 (**Table 2**). Generally, pH seems to be the main factor shaping Chironomidae composition in each typology. Besides that, redundancy analyses revealed the importance of K and organic matter (**Figure 4**). In W3(2) samples, pH is strongly correlated (0.88) with diatom concentration (**Supplementary Figure 1**), while they are absent from the W4 sequence.

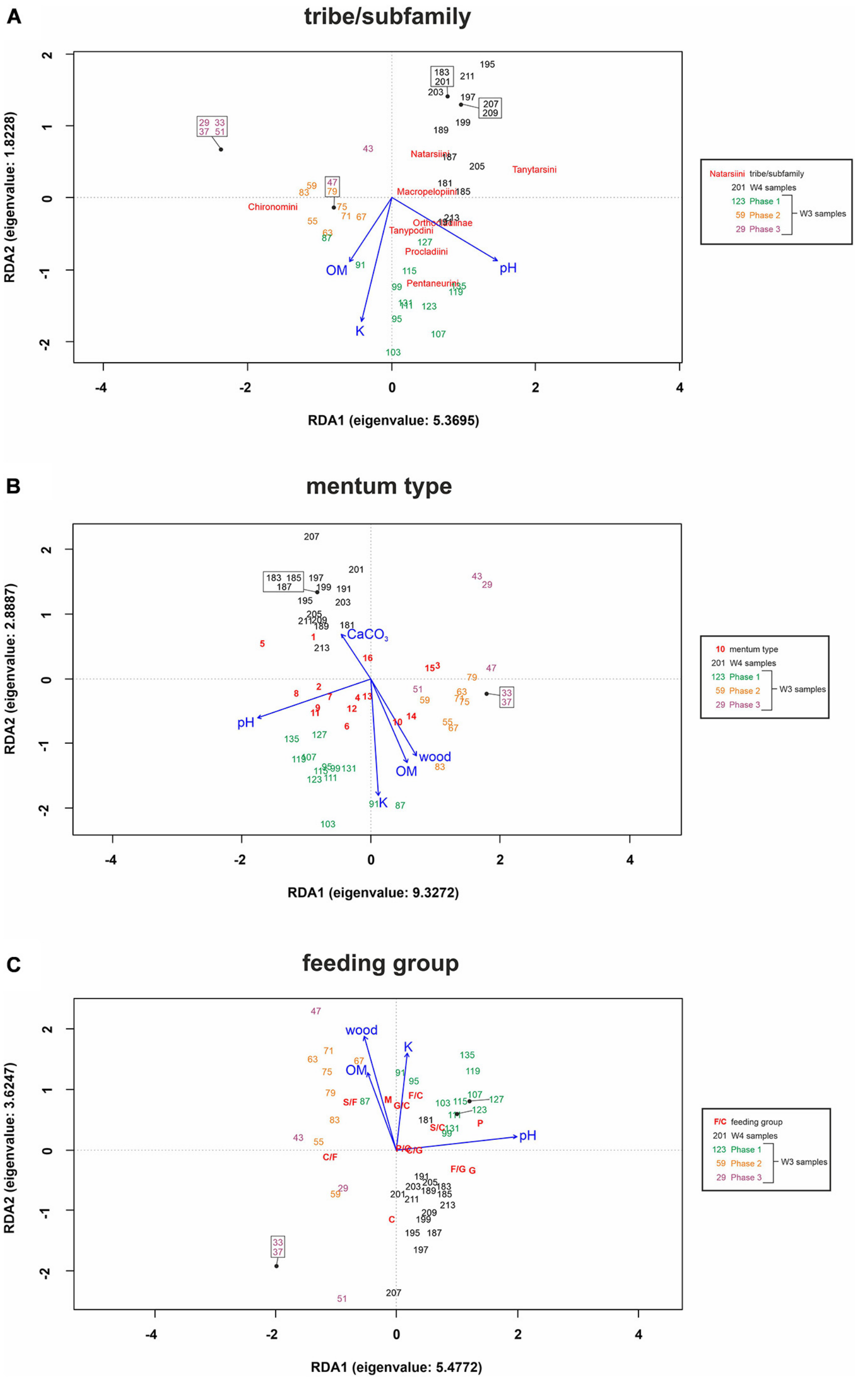


FIGURE 4 | Redundancy Analysis for tribes/subfamilies **(A)**, mentum types **(B)** and feeding groups **(C)** showing composition differences according to selected environmental factors (blue) in samples within two cores [W3(2) and W4]. The abbreviations used for functional feeding groups were as follows: C – collector-gatherers; C/F – collector-filterers; C/G – collectors/grazers; S/F – shredders/filterers; S/C – shredders/collectors; G – grazers/scrapers; G/C – grazers/collectors; F/C – filterers/collectors; F/G – filterers/grazers; M – miners; P – predators; and P/C – predators/collectors. The symbols used for morphological types are explained in **Table 1**. For full names of variables, see **Supplementary Table 1**.

This is the reason why, although they are an important food source for some chironomid larvae, they were not included in the analysis. Another important factor is *Urtica dioica,* which reveals higher significance treated individually in the hierarchical partitioning than in the averaged GLMs.

All combinations of the most parsimonious models used to compute average models for each analysis are listed in

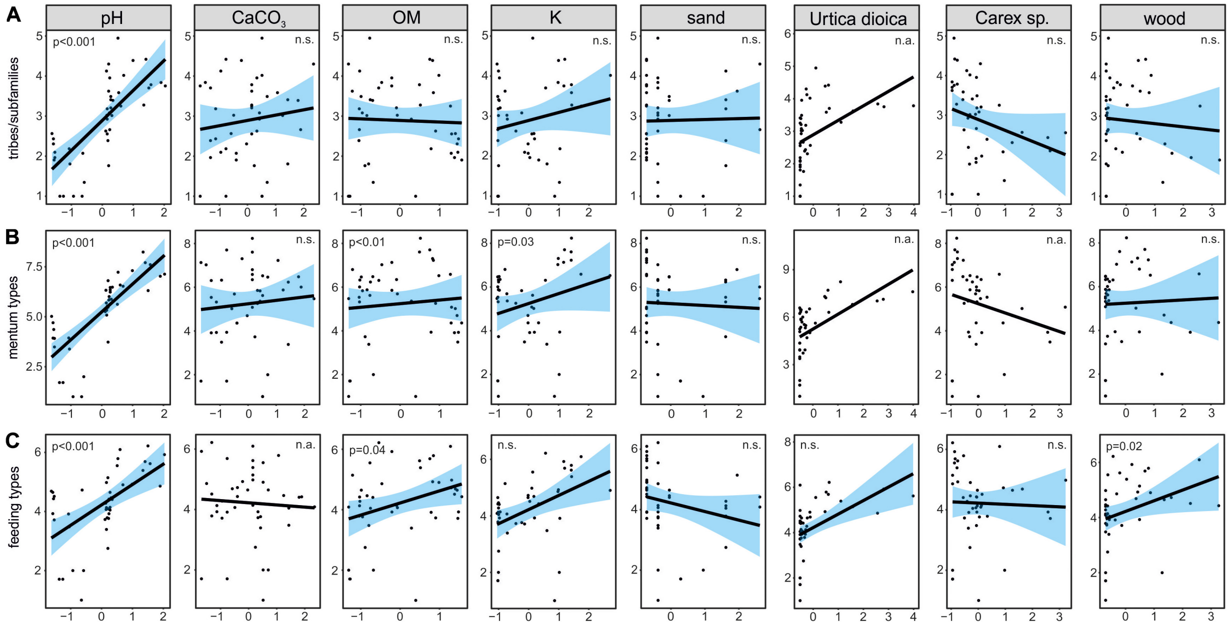


FIGURE 5 | Visualization of generalized linear models testing for effects of selected environmental factors on richness of chironomid tribes/subfamilies **(A)**, mentum types **(B)** and feeding type **(C)**, where "n.a." means that the factor was not included in the models, and "n.s." that its explanatory power was not significant.

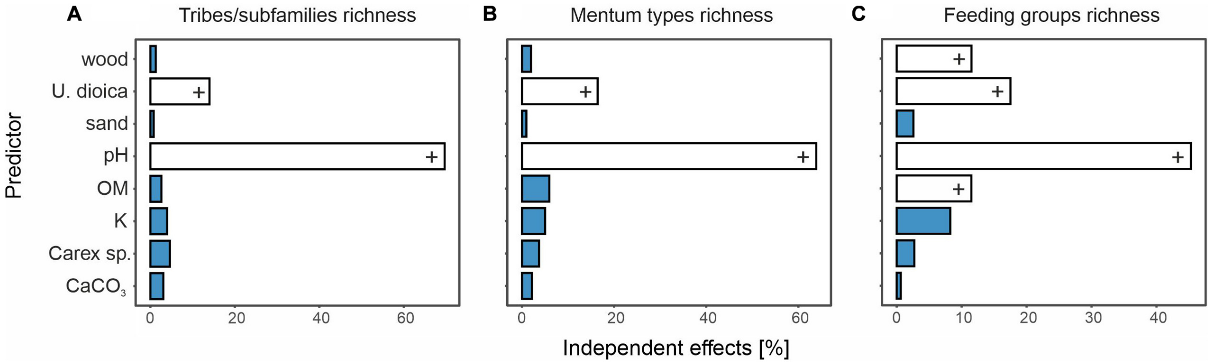


FIGURE 6 | Relative contribution of each predictor to shared variability of full models testing for effects of environmental factors and richness of tribes/subfamilies **(A)**, mentum types **(B)**, and feeding types **(C)**. A positive impact of environmental variables was marked with a plus (+) and negative impact with a minus (–). Predictors with statistical significance of response variables are given in white. For full predictor names, see **Supplementary Table 1**.

Supplementary Table 2. For final values of each environmental factor in averaged models, see **Supplementary Table 3**.

DISCUSSION

Chironomidae Habitat Preferences in the Paleo-Oxbow and the Moat

Both generalized linear models (**Figure 5**) and hierarchical partitioning (**Figure 6**) clearly show that the crucial factors shaping Chironomidae functional composition are pH and OM. However, each site is different, depending on the levels of these factors. In the paleochannel (W4), pH was stable and circum-neutral, as indicated by the geochemical analysis. That provided favorable conditions for a complex, functionally diverse ecosystem. In the moat system (W3), pH conditions underwent significant change, from slightly alkaline in the first phase of its development to slightly acidic in the following phases. Those changes are associated with primary human-induced eutrophication and water acidification after ringfort abandonment (Kittel et al., 2018a; **Figure 4**). The K, OM, and wood positively shaped Chironomidae assemblages in the first phase of moat development, during human settlement in the ringfort (Kittel et al., 2018a). Taxa typical of permanent stagnant, partly overgrown water bodies (e.g., *Paratanytarsus penicillatus*-type, *Glyptotendipes pallens*-type and *Cricotupus intersectus*-type) were dominant. Mining chironomids were represented mainly by *Endochironomus tendens*-type and *Glyptotendipes pallens*-type.

In the group of eutrophic species that are mining several macrophyte species (as *Endochironomus impar*-type in Berg, 1995; Beiger, 2004; Moller Pillot, 2009), many just live in coarse organic detritus, without direct association with living plant tissue (Bijlmakers, 1983). Tóth et al. (2012) state that the above-mentioned chironomids are in fact mostly opportunistic in selecting macrophyte species, while the structure of vegetation is more important. They could also settle on decaying wood particles, bark and small branches. Among terrestrial plants, *Urtica dioica* is strongly correlated with chironomid community richness according to its independent effect (**Figure 6**). This is an indicator of wet, nitrogen-rich soil (Hill et al., 1999). *Urtica* is often found in swampy habitats, but also in great abundance in habitats where high trophic state is the result of human impact (Šrùtek and Teckelmann, 1998). Both *Urtica* abundance and Chironomidae species richness result from high trophic conditions in the moat (high OM and pH) (**Figure 6**). Potassium (K) that shaped communities with high significance, indirectly marks denudation processes associated with human influence on the moat, in its first stage of development (W3). The ringfort surroundings were strongly exposed to trampling, lithogenic elements were also moved from local gardens and fields (Kittel et al., 2018a). Denudation processes influenced moat bank habitats affecting chironomid communities even on a high taxonomic level. These processes are associated with the inwash of organic and inorganic suspension, including fine particulate organic matter. Thus, the filtrators and collector-gatherers were abundant. The moat history ends with a sudden decrease of Chironomidae abundance and its transformation into the semiterrestrial peaty habitat (low pH but high OM, K, and wood accumulation) (**Figure 4**). It is associated with the complete change of the conditions in the moat, which were no longer favorable for most chironomid taxa. The scarcity of water, acidification, and macrophyte composition transformation meant that only taxa adapted to such conditions could survive. Within the chironomid fauna of that time, there were single individuals of *Limnophyes-Paralimnophyes*, *Pseudosmittia,* and *Pseudorthocladius* (mentum type 15), along with some Chironominae (mostly collectors) typical of muddy bottoms of the retain ditch of the moat (Kittel et al., 2018a).

Whereas the samples from W3(2) are more scattered and arranged according to depth, the W4 samples are aggregated closely together in the ordination analysis (**Figure 4**). This results from the habitat conditions in the paleochannel (W4) during Late Weichselian, which were more uniform and stable for a long time than in the moat habitat. They reveal significantly lower importance of lithogenic elements (like K) than in W3(2), indicating that Medieval human settlement in the valley caused higher denudation than during Allerød-Younger Dryas transition. Lower trophic state in this case does not follow acidification like in W3(2) but comes from generally low OM content in the Lateglacial landscape (Birks and Birks, 2004). Initial plant communities (Feurdean et al., 2014) did not generate much wood substrate for the mining chironomid communities. The morphological traits varied across the $CaCO_3$ gradient from W3(2) to W4 mostly due to its high content in W4, as opposed to low content in W3(2). The influence of this variable on chironomids is associated with the periods of increased leaching from the shallow groundwater. During the Late Glacial oxbows in the regional river valleys were supplied by carbonate groundwater (Płóciennik et al., 2015; Pawłowski et al., 2016a). The water supply (precipitation, floods, and groundwater) is important for the biota composition in river valley wetlands. When groundwater seeps to the oxbows there appear taxa typical to cold, alkaline springs and brooks (Płóciennik et al., 2015; Pawłowski et al., 2016b).

Despite covering a similar timespan (ca. 600 years), out of both studied cores, the W3(2) sequence was far more ecologically diverse. Without doubt, human impact was crucial here. It changed both physical and chemical water composition, and thus also flora and fauna within the moat system and in its immediate vicinity (Kittel et al., 2018a). Ringfort inhabitants supplied the moat system with a significant amount of wood (mostly *Quercus* sp.), which served as a hard substrate for periphyton, including diatoms. This way, even if it was not a direct food source for the xylophiles, it created a suitable microhabitat for a range of trophic guilds, mostly scrapers. Such coarse organic matter is important not only for phytophilous grazers and filter feeders (such as *Glyptotendipes pallens*-type and *Dicrotendipes nervosus*-type) but also for collector-gatherers and shredders, represented here by larvae with mentum types 12 and 14 (*Polypedilum, Phaenopsectra,* and *Endochironomus*). Lower habitat variability and higher environmental stability (manifested here, e.g., by the narrow pH gradient) in the paleo-oxbow implied lower diversity of chironomid groups. In the W4 sequence, only 15 (out of 16) mentum types and 10 (out of 12) functional feeding groups were recorded (**Figure 3**).

Comparison of Typologies

It is not surprising that the results of ordination analyses based on three Chironomidae typologies are to some extent convergent. They reveal similar trends as they are based on the same data, though classified differently. However, mentum types and FFGs allow for a more detailed ecological interpretation than tribe classification. As feeding ecology strongly influenced mouthparts evolution, FFGs may aggregate taxa phylogenetically distant but having similar mouthparts (Armitage et al., 1995). Among the examples are Procladiini and *Cryptochironomus* with a similar, concave mentum, belonging to two different subfamilies, semiterrestrial Orthocladiinae representing different genera, and phytophile taxa from mentum types 10 and 12. The mentum shape fits feeding ecology across the taxonomic classification, as can be seen in the stratigraphic diagrams presented in **Figure 3**. The FFGs and mentum type stratigraphy are consistent, because habitat transformations cause changes in the available food – from suitable for P and G throughout G/C, C/F, and M typical of eutrophic, overgrown shallow water, to C and C/F living in wet moss and soil, and thus having a different food base. In fact, chironomid communities often consist of taxa with a similar type of mentum according to habitat conditions (pers. obs.).

Functional Groups as Habitat Indicators

Chironomidae functional traits have so far been studied mainly by Serra et al. (2016, 2017), who developed a trait database for

European genera, analyzed it for subfamilies and compared it with the North American database (USEPA, 2012). However, such a taxonomic level seems to be too general for several traits. Creating such a database for larvae morphotypes, commonly used in paleolimnology, is worth considering.

Birks (2020) indicates that the functional trait approach in plant paleoecology has several limitations. While pollen-based ecological information is generalized, as it often can be identified only to the family or genus level, plant macrofossil analyses are problematic because of mixed data types and the possibility of 'false absences' (Birks, 2014, 2020). Here, chironomid subfossils could play a significant complementing role. The functional groups approach seems to work well in microhabitat reconstructions. Chironomidae FFGs and mentum types correspond to several environmental factors, such as the substrate and vegetation type, as well as physicochemical conditions. Although dividing taxa into groups is itself a generalization and may lead to loss of some data, it is also an easier and more systematized method to obtain comparable results. As functional guilds work well in climate reconstructions (see Kivilä et al., 2019), why not use them in tracking changes in the habitat structure? The chironomids serve well at the morphotype level as indicators of habitat complexity in terms of plant richness and density (Langdon et al., 2010). In fact, their association with vegetation is generally established within FFGs and, most likely, also morphological groups.

In this study, we classified each recorded Chironomidae morphospecies to a morphological group. The groups were distinguished on the basis of mentum and ventromental plates, as these elements are usually preserved well in the sediment. Whereas this classification may be enhanced and complemented in the future, it may serve as a good surrogate for functional feeding groups in habitat reconstructions. However, we need to be aware that, while the mouthpart type is strongly associated with feeding behavior, it is not the only factor shaping it. Mouthpart morphology is associated with many aspects of species biology and ecology, so it is not as strong an indicator of habitat changes as feeding groups. Moreover, as food preferences may change throughout life of chironomid larvae, only the 3rd and 4th instars should be included in such analyses. In fact, head capsules of the 1st and 2nd instars of chironomid larvae hardly ever preserve well in the sediment. In the future, the feeding groups and morphological types should also be tested within the contemporary assemblages ranging through measured ecological gradients. It would give a picture of more direct linkages between chironomid larvae and their habitat.

CONCLUSION

The results indicate that Chironomidae FFGs and morphological types reveal similar reactions to the biotic and abiotic environmental factors. Thus, they could serve as surrogate indicators where applicable. A well-designed mouthpart typology would be an easy and systematized method to obtain basic results comparable with functional feeding groups. Chironomidae morphological types can be easily recognized, e.g., during plant or beetle macrofossil analysis, and pre-analyzed without knowing the exact ecology of each taxon. If such preliminary examination give promising results, further detailed analysis should be undertaken by a specialist. Such an approach would enable the implementation of Chironomidae analyses in a wider range of paleolimnological and archeological research. The trait-based approach in subfossil Chironomidae studies is worth developing and can prove useful in the future application in paleolimnology. The potential use of morphological types should be checked during further studies based on modern Chironomidae assemblages ranging through known ecological gradients.

To conclude, such simplified para-taxonomic analyses based on generalized morphological types never fully replace detailed species-specific autecological approach. However, in cases where a comprehensive chironomid study is not possible, the proposed method can serve as a useful tool to obtain some ecological information.

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DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

OA-O and MP conceived the study. RS-R, MR, and DO contributed paleobotanical and geochemical data. PK analyzed the geomorphology and paleogeography of the area and conducted the fieldwork at the study site. MK provided radiocarbon and dendrological dates. RS provided statistical analyses. OA-O, RS, and MP interpreted the data and wrote the manuscript with contributions from all authors. RS, OA-O, AM, and PK created the figures. JS, AM, and MS edited the final manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2020.583831/full#supplementary-material

Supplementary Figure 1 | Correlation matrices with Pearson's r correlation coefficients calculated for the W3(2) core: **(A)** all predictors and **(B)** predictors left for further analyses. For full predictor names, see **Supplementary Table 1**.

Supplementary Figure 2 | Correlation matrices with Pearson's r correlation coefficients calculated for the W4 core: **(A)** all predictors and **(B)** predictors left for further analyses. For full predictor names, see **Supplementary Table 1**.

Supplementary Table 1 | Variables for cores analyzed in the study. The data was standardized during analyses. Bolded variables were included in further analysis.

Supplementary Table 2 | Most supported (ΔAIC < 2) models testing for impact of environmental factors on richness of chironomid groups in each typology.

Supplementary Table 3 | Impact of environmental factors used in averaged models on richness of analyzed chironomid groups (generalized linear regression).

REFERENCES

Alfons, A. (2019). *robustHD: Robust Methods for High-Dimensional Data. R package version 0.6.1*. https://CRAN.R-project.org/package=robustHD.

Andersen, T., Cranston, P. S., and Epler, J. H. (2013). Chironomidae of the Holarctic region: keys and diagnoses. Part 1. Larvae. *Insect Syst. Evol. Suppl.* 66, 1–571. doi: 10.11646/zootaxa.60.1.1

Armitage, P. D., Cranston, P. S., and Pinder, L. C. V. (1995). *The Chironomidae. Biology and Ecology of Non-biting Chironomids*. London: Chapman & Hall.

Barboni, D., Harrison, S. P., Bartlein, P. J., Jalut, G., New, M., and Prentice, I. C. (2004). Relationships between plant traits and climate in the Mediterranean region: a pollen data analysis. *J. Veg. Sci.* 15, 635–646. doi: 10.1111/j.1654-1103.2004.tb02305.x

Bartoń, K. (2018). *MuMIn: Multi-model Inference. R package version 1.42.1*. https://CRAN.R-project.org/package=MuMIn.

Battarbee, R. W. (1986). "Diatom analysis," in *Handbook of Holocene Paleoecology and Paleohydrology*, ed. B. E. Berglund (Chichester: John Wiley and Sons ltd), 527–570.

Battarbee, R. W., and Kneen, M. J. (1982). The use of electronically counted microspheres in absolute diatom analysis. *Limnol. Oceanogr.* 27, 184–188. doi: 10.4319/lo.1982.27.1.0184

Beiger, M. (2004). *Owady minujące Polski. Klucz do oznaczania na podstawie min*. Poznań: Bogucki Wydawnictwo Naukowe.

Berg, M. B. (1995). "Larval food and feeding behaviour," in *The Chironomidae: Biology and Ecology of Non-biting Chironomids*, eds P. D. Armitage, P. S. Cranston, and L. V. Pinder (London: Chapman and Hall), 136–198. doi: 10.1007/978-94-011-0715-0_7

Berggren, G. (1981). *Atlas of seeds and small fruits of Northwest European plant species (Sweden, Norway, Denmark, East Fennoscandia and Iceland) with morphological descriptions, part 3*. Berlings: Salicaceae-Cruciferae.

Bijlmakers, L. (1983). *De verspreiding en oecologie van chironomide larven (Chironomidae: Diptera) in twee vennen in de omgeving van Oisterwijk (N.Br.)*. Versl: K.U. Nijmegen.

Birks, H. J. B. (2014). Challenges in the presentation and analysis of plant macrofossil stratigraphical data. *Veget. History Archaeobot.* 23, 309–330. doi: 10.1007/s00334-013-0430-2

Birks, H. J. B. (2020). Reflections on the Use of Ecological Attributes and Traits in Quaternary Botany. *Front. Ecol. Evolut.* 8, 1–13. doi: 10.3389/fevo.2020.00166

Birks, H. J. B., and Birks, H. H. (2004). *Quaternary palaeoecology*. Caldwell, N.J: Blackburn Press.

Brooks, S. J., Bennion, H., and Birks, H. J. B. (2001). Tracing lake trophic history with a chironomid-total phosphorus inference model. *Freshw. Biol.* 46, 513–533. doi: 10.1046/j.1365-2427.2001.00684.x

Brooks, S. J., Langdon, P. G., and Heiri, O. (2007). The identification and use of Palaearctic Chironomidae larvae in palaeoecology. *Quat. Res. Assoc.* 53, 2129–2130. doi: 10.1111/j.1365-2427.2007.01926.x

Cappers, R. T. J., Bekker, R. M., and Jans, J. E. A. (2006). *Digital seed atlas of the Netherlands*. Groningen: Groningen University Library.

Carvalho, F. A., Brown, K. A., Waller, M. P., Bunting, M. J., Boom, A., and Leng, M. J. (2019). A method for reconstructing temporal changes in vegetation functional trait composition using Holocene pollen assemblages. *PLoS One* 14:e0216698. doi: 10.1371/journal.pone.0216698

Clift, P. D., Olson, E. D., Lechnowskyj, A., Moran, M. G., Barbato, A., and Lorenzo, J. M. (2019). Grain-size variability within a mega-scale point-bar system. *False Riv. Louis. Sedimentol.* 66, 408–434. doi: 10.1111/sed.12528

Díaz, S., and Cabido, M. (2001). Vive la différence: plant functional diversity matters to ecosystem processes. *Trends Ecol. Evol.* 16, 646–655. doi: 10.1016/S0169-5347(01)02283-2

Đurđević, A., Savić, D., Lazarević, M., Žikić, V., and Milošević, D. (2017). "Can we guess the autecology following the variability of mandible shape in the Chironomidae family?," in *20th International Symposium on Chironomidae. Abstract Book of the 20th International Symposium on Chironomidae*, ed. V. Lencioni (Groningen: Groningen University Library), 64.

Ferrington, L. C. (2008). Global diversity of non-biting chironomids (Chironomidae. Insecta-Diptera) in freshwater. *Hydrobiologia* 595, 447–455. doi: 10.1007/978-1-4020-8259-7_45

Feurdean, A., Perşoiu, A., Tanţău, I., Stevens, I., and Magyari, E. K. (2014). Climate variability and associated vegetation response throughout Central and Eastern Europe (CEE) between 60 and 8 ka. *Quat. Sci. Rev.* 106, 206–224. doi: 10.1016/j.quascirev.2014.06.003

Fournier, B., Lara, E., Jassey, V. E. J., and Mitchell, E. A. D. (2015). Functional traits as a new approach for interpreting testate amoeba palaeo-records in peatlands and assessing the causes and consequences of past changes in species composition. *Holocene* 25, 1375–1383. doi: 10.1177/0959683615585842

Fox, J., and Weisberg, S. (2011). *An {R} Companion to Applied Regression, Second Edition*. Thousand Oaks CA: Sage.

Franquet, E. (1999). Chironomid assemblage of a Lower-Rhone dike field: relationships between substratum and biodiversity. *Hydrobiologia* 397, 121–131.

Frouz, J. (1999). Use of soil dwelling Diptera (Insecta, Diptera) as bioindicators: a review of ecological requirements and response to disturbance. *Agricult. Ecosyst. Environ.* 74, 167–186. doi: 10.1016/b978-0-444-50019-9.50013-3

Gandouin, E., Maasri, A., Van Vliet-Lano, B., and Franquet, E. (2006). Chironomid (Insecta: Diptera) assemblages from a gradient of lotic and lentic waterbodies in river floodplains of France: a methodological tool for paleoecological applications. *J. Paleolimnol.* 35, 149–166. doi: 10.1007/s10933-005-8149-4

Garnier, E., Lavorel, S., Ansquer, P., Castro, H., Cruz, P., and Dolezal, J. (2007). Assessing the effects of land-use change on plant traits, communities and ecosystem functioning in grasslands: a standardized methodology and lessons from an application to 11 European sites. *Anna. Bot.* 99, 967–985. doi: 10.1093/aob/mcl215

Goździk, J. (1982). Środowisko przyrodnicze osadnictwa średniowiecznego okolic Rozprzy. Prace i Materiały Muzeum Archeologicznego i Etnograficznego w śodzi. *Ser. Archeol.* 29, 138–151.

Gregory-Eaves, I., and Beisner, B. E. (2011). Palaeolimnological insights for biodiversity science: An emerging field. *Freshwater Biol.* 56, 2653–2661. doi: 10.1111/j.1365-2427.2011.02677.x

Greguss, P. (1945). *The identification of Central-European dicotyledonous trees and shrubs based on xylotomy*. Budapest: Hungarian Museum of Natural History.

Grosser, D. (1977). *Die Hölzer Mitteleuropas. Ein mikrophotographischer Lehratlas*. Berlin: Springer-Verlag.

Heiri, O., Brooks, S. J., Birks, H. J. B., and Lotter, A. F. (2011). A 274-lake calibration data-set and inference model for chironomid-based summer air temperature reconstruction in Europe. *Quat. Sci. Rev.* 30, 3445–3456. doi: 10.1016/j.quascirev.2011.09.006

Heiri, O., Lotter, A. F., and Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *J. Paleolimnol.* 25, 101–110.

Henrikson, L., Olafsson, J. B., and Oscarson, H. G. (1982). The impact of acidification on Chironomidae (Diptera) as indicated by subfossil stratification. *Hydrobiologia* 86, 223–229. doi: 10.1007/bf00006140

Hill, M. O., Mountford, J. O., Roy, D. B., and Bunce, R. G. H. (1999). *Ellenberg's indicator values for British plants. ECOFACT Volume 2 Technical Annex*. Huntingdon: Institute of Terrestrial Ecology.

Howard, L. C., Wood, P. J., Greenwood, M. T., Rendell, H. M., Brooks, S. J., Armitage, P. D., et al. (2010). Subfossil Chironomidae as indicators of palaeoflow regimes: integration into the PalaeoLIFE flow index. *J. Quat. Sci.* 25, 1270–1283. doi: 10.1002/jqs.1409

Jiang, X., Pan, B., Song, Z., and Xie, Z. (2019). Do functional traits of chironomid assemblages respond more readily to eutrophication than taxonomic composition in Chinese floodplain lakes? *Ecol. Indicat.* 103, 355–362. doi: 10.1016/j.ecolind.2019.04.029

Juggins, S. (2007). *C2 version 1.5 user guide. Software for Ecological and Palaeoecological Data Analysis and Visualisation*. Newcastle upon Tyne: Newcastle University.

Kats, N. Y., Kats, S. V., and Kipiani, M. G. (1965). *Atlas i opredelitel' plodov i semyan vstrechayushchikhsya v chetviertichnykh otlozheniyach SSSR*. Izdat: Nauka.

Kearney, M., Simpson, S. J., Raubenheimer, D., and Helmuth, B. (2010). Modelling the ecological niche from functional traits. *Phil. Trans. R. Soc. B* 365, 3469–3483. doi: 10.1098/rstb.2010.0034

Kittel, P., Płóciennik, M., Borówka, R. K., Okupny, D., Pawłowski, D., Peyron, O., et al. (2016). Early Holocene hydrology and environments of the Ner River (Poland). *Quat. Res.* 85, 187–203. doi: 10.1016/j.yqres.2015.12.006

Kittel, P., Sikora, J., and Wroniecki, P. (2015). The morphology of the Luciąża River valley floor in the vicinity of the Rozprza medieval ring-fort in light of geophysical survey. *Bull. Geogr. Phys. Geogr. Ser.* 8, 95–106. doi: 10.1515/bgeo-2015-0008

Kittel, P., Sikora, J., and Wroniecki, P. (2018b). A Late Medieval motte-and-bailey settlement in a lowland river valley landscape of central Poland. *Geoarchaeology* 33, 558–578. doi: 10.1002/gea.21676

Kittel, P., Sikora, J., Antczak, O., Brooks, S. J., Elias, S. A., Krąpiec, M., et al. (2018a). The palaeoecological development and functioning of the Late Medieval moat – multiproxy research at Rozprza. *Centr. Poland. Quart. Int.* 482, 131–156. doi: 10.1016/j.quaint.2018.03.026

Kivilä, E. H., Luoto, T. P., Rantala, M. V., and Nevalainen, L. (2020). Late-Holocene variability in chironomid functional assemblages and carbon utilization in a tundra lake food web. *Hydrobiologia* 847, 895–911. doi: 10.1007/s10750-019-04151-7

Kivilä, E. H., Luoto, T. P., Rantala, M. V., Kiljunen, M., Rautio, M., and Nevalainen, L. (2019). Environmental controls on benthic food web functions and carbon resource use in subarctic lakes. *Freshwater Biol.* 64, 643–658. doi: 10.1111/fwb.13250

Kleyer, M., Dray, S., Bello, F., Lepš, J., Pakeman, R. J., Strauss, B., et al. (2012). Assessing species and community functional responses to environmental gradients: which multivariate methods? *J. Veget. Sci.* 23, 805–821. doi: 10.1111/j.1654-1103.2012.01402.x

Kotrys, B., Płóciennik, M., Sydor, P., and Brooks, S. J. (2020). Expanding the Swiss-Norwegian chironomid training set by incorporating Polish data and assessing its transfer function capability using temperature reconstructions from Lake Żabieniec. *Boreas* 49, 89–107.

Lamentowicz, M., Forysiak, J., Balwierz, Z., Płóciennik, M., Kittel, P., Kloss, M., et al. (2009). Multiproxy study of anthropogenic and climatic changes in the last two millennia from a small mire in central Poland. *Hydrobiologia* 631, 213–230. doi: 10.1007/978-90-481-3387-1_13

Lamentowicz, M., Gałka, M., Lamentowicz, Ĺ, Obremska, M., Kühl, N., Lücke, A., et al. (2015). Reconstructing climate change and ombrotrophic bog development during the last 4000 years in northern Poland using biotic proxies, stable isotopes and trait-based approach. *Palaeog. Palaeocl. Palaeoecol.* 418, 261–277. doi: 10.1016/j.palaeo.2014.11.015

Langdon, P. G., Ruiz, Z., Wynne, S., Sayer, C. D., and Davidson, T. A. (2010). Ecological influences on larval chironomid communities in shallow lakes: implications for palaeolimnological interpretations. *Freshwat. Biol.* 55, 531–545. doi: 10.1111/j.1365-2427.2009.02345.x

Luoto, T. P. (2009a). A Finnish chironomid- and chaoborid-based inference model for reconstructing past lake levels. *Quat. Sci. Rev.* 28, 1481–1489. doi: 10.1016/j.quascirev.2009.01.015

Luoto, T. P. (2009b). Subfossil Chironomidae (Insecta: Diptera) along a latitudinal gradient in Finland: development of a new temperature inference model. *J. Quat. Sci.* 24, 150–158. doi: 10.1002/jqs.1191

Marcisz, K., Jassey, V. E. J., Kosakyan, A., Krashevska, V., Lahr, D. J. G., and Lara, E. (2020). Testate Amoeba Functional Traits and Their Use in Paleoecology. *Front. Ecol. Evol* 8, 1–28. doi: 10.3389/fevo.2020.575966

Marks, L. (2011). "Quaternary Glaciations in Poland," in *Developments in Quaternary Sciences 15*, eds J. Ehlers, P. L. Gibbard, and P. D. Hughes (Izdat: Nauka), 299–303. doi: 10.1016/b978-0-444-53447-7.00023-4

Matuszkiewicz, J. M. (2008). *Potencjalna roślinność naturalna Polski (Potential natural vegetation of Poland), IGiPZ PAN, Warszawa*. Available online at: http://www.igipz.pan.pl/Roslinnosc-potencjalna-zgik.html (accessed on March 10, 2017)

Milošević, D., Stojanović, K., Djurdjević, A., Marković, Z., Stojković Piperac, M., Živić, M., et al. (2018). The response of chironomid taxonomy- and functional trait-based metrics to fish farm effluent pollution in lotic systems. *Environ. Pollut.* 242, 1058–1066. doi: 10.1016/j.envpol.2018.07.100

Moller Pillot, H. K. M. (2009). *Chironomidae larvae. Biology and Ecology of the Chironomini*. Zeist: KNNV Publishing.

Moller Pillot, H. K. M. (2013). *Chironomidae larvae of the Netherlands and adjacent lowlands, Biology and Ecology of the aquatic Orthocladiinae, Prodiamesinae, Diamesinae*. Buchonomyiinae: KNNV Publishing.

Monakov, A. V. (1972). Review of studies on feeding of aquatic invertebrates conducted at the Institute of Biology of Inland Waters, Academy of Science, USSR. *J. Fisher. Res. Board Can.* 29, 363–383. doi: 10.1139/f72-064

Motta, L., and Massaferro, J. (2019). Climate and site-specific factors shape chironomid taxonomic and functional diversity patterns in northern Patagonia. *Hydrobiologia* 839, 131–143. doi: 10.1007/s10750-019-04001-6

Mycielska-Dowgiałło, E., and Ludwikowska-Kêdzia, M. (2011). Alternative interpretations of grain-size data from Quaternary deposits. *Geologos* 17, 189–203.

Nevalainen, L., and Luoto, T. P. (2017). Relationship between cladoceran (Crustacea) functional diversity and lake trophic gradients. *Funct. Ecol.* 31, 488–498. doi: 10.1111/1365-2435.12737

Nevalainen, L., Luoto, T. P., Manca, M., and Weisse, T. (2015). A paleolimnological perspective on aquatic biodiversity in Austrian mountain lakes. *Aquat. Sci.* 77, 59–69. doi: 10.1007/s00027-014-0363-6

Ni, Z., Zhang, E., Herzschuh, U., Mischke, S., Chang, J., Sun, W., et al. (2020). Taxonomic and functional diversity differentiation of chironomid communities in northern Mongolian Plateau under complex environmental impacts. *Hydrobiologia* 847, 2155–2167. doi: 10.1007/s10750-020-04241-x

Nock, C. A., Vogt, R. J., and Beisner, B. E. (2016). *Functional Traits. eLS*. Chichester: John Wiley & Sons, Ltd, doi: 10.1002/9780470015902.a0026282

Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., et al. (2019). *Vegan: Community Ecology Package. R package version 2.5-4*. https://CRAN.R-project.org/package=vegan.

Olafsson, J. S. (1992). A comparative study on mouthpart morphology of certain larvae of Chironomini (Diptera: Chironomidae) with a reference to the larval feeding habits. *J. Zool. Lond.* 228, 183–204. doi: 10.1111/j.1469-7998.1992.tb04602.x

Pawłowski, D., Borówka, R. K., Kowalewski, G., Luoto, T. P., Milecka, K., Nevalainen, L., et al. (2016a). Late Weichselian and Holocene record of the paleoenvironmental changes in a small river valley in Central Poland. *Quat. Sci. Rev.* 135, 24–40. doi: 10.1016/j.quascirev.2016.01.005

Pawłowski, D., Borówka, R. K., Kowalewski, G., Luoto, T. P., Milecka, K., Nevalainen, L., et al. (2016b). The response of flood-plain ecosystems to the Late Glacial and Early Holocene hydrological changes: a case study from a small Central European river valley. *Catena* 147, 411–428. doi: 10.1016/j.catena.2016.07.034

Pla, L., Casanoves, F., and Di Rienzo, J. (2012). "Functional Diversity Indices," in *L. Pla, F. Casanoves and J. Di Rienzo. SpringerBriefs in Environmental Science*, Quantifying Functional and Biodiversity (Dordrecht: Springer), 27–51. doi: 10.1007/978-94-007-2648-2_3

Płóciennik, M., Kruk, A., Forysiak, J., Pawłowski, D., Mianowicz, K., Elias, S., et al. (2015). Fen ecosystem response to water-level fluctuations during the early and middle Holocene in Central Europe: a case study from Wilczków. *Poland. Boreas* 44, 721–740. doi: 10.1111/bor.12129

Płóciennik, M., Pawłowski, D., Vilizzi, L., and Antczak-Orlewska, O. (2020). From oxbow to mire: Chironomidae and Cladocera as habitat palaeoindicators. *Hydrobiologia* 847, 3257–3275. doi: 10.1007/s10750-020-04327-6

Porinchu, D. F., and MacDonald, G. M. (2003). The use and application of freshwater chironomids (Chironomidae: Insecta: Diptera) in geographical research. *Progr. Geogr.* 27, 378–422. doi: 10.1191/030913303767888491

R Core Team (2020). *R: A language and environment for statistical computing*. Austria: R Foundation for Statistical Computing.

Reitalu, T., Gerhold, P., Poska, A., Pärtel, M., Väli, V., and Veski, S. (2015). Novel insights into post-glacial vegetation change: functional and phylogenetic diversity in pollen records. *J. Veg. Sci.* 26, 911–922. doi: 10.1111/jvs.12300

Rolland, N., and Larocque, I. (2007). The efficiency of kerosene flotation for extraction of chironomid head capsules from lake sediments samples. *J. Paleolimnol.* 37, 565–572. doi: 10.1007/s10933-006-9037-2

Saether, O. A. (1979). Chironomid communities as water quality indicators. *Holarctic Ecol.* 2, 65–74. doi: 10.1111/j.1600-0587.1979.tb00683.x

Schiffels, S. (2014). Commensal and parasitic Chironomidae. *Denisia* 163, 393–407.

Schmid, P. E. (1993). *A key to the Chironomidae and their instars from Austrian Danube region streams and rivers. Part I, Diamesinae, Prodiamesinae and Orthocladiinae*. Wien: Federal Institute for Water Quality of the Ministry of Agriculture and Forestry.

Schweingruber, F. H. (1978). *Mikroskopische Holzanatomie. Swiss Federal Institute of Forestry Research, Birmensdorf*. Wien: Federal Institute for Water Quality of the Ministry of Agriculture and Forestry.

Schweingruber, F. H., Börner, A., and Schulze, E.-D. (2011). *Atlas of Stem Anatomy in Herbs, Shrubs and Trees*, Vol. 1. Heidelberg: Springer.

Serra, S. R. Q., Cobo, F., Graça, M. A. S., Dolédec, S., and Feio, M. J. (2016). Synthesising the trait information of European Chironomidae (Insecta: Diptera): Toward a new database. *Ecol. Indicat.* 61, 282–292. doi: 10.1016/j.ecolind.2015.09.028

Serra, S. R. Q., Graça, M. A. S., Dolédec, S., and Feio, M. J. (2017). Chironomidae of the Holarctic region: a comparison of ecological and functional traits between North America and Europe. *Hydrobiologia*. 794, 273–285. doi: 10.1007/s10750-017-3102-x

Sikora, J., Kittel, P., and Wroniecki, P. (2015). From a point on the map to a shape in the landscape. Non-invasive verification of medieval ring-forts in Central Poland: Rozprza case study. *Archaeol. Pol.* 53, 510–514.

Sikora, J., Kittel, P., Frączek, M., Głąb, Z., Golyeva, A., Mueller-Bieniek, A., et al. (2019). A palaeoenvironmental reconstruction of the rampart construction of the medieval ring-fort in Rozprza. *Centr. Pol. Archaeol. Anthropol. Sci.* 11, 4187–4219. doi: 10.1007/s12520-018-0753-0

Spies, M. (2005). On selected family group names in Chironomidae (Insecta, Diptera), and related nomenclature. *Zootaxa* 894, 1–12. doi: 10.11646/zootaxa.894.1.1

Šrùtek, M., and Teckelmann, M. (1998). Review of biology and ecology of *Urtica dioica*. *Presha* 70, 1–19. doi: 10.2307/2255757

Stuart-Smith, R., Bates, A., Lefcheck, J., Duffy, E., Baker, S. C., Thomson, R. J., et al. (2013). Integrating abundance and functional traits reveals new global hotspots of fish diversity. *Nature* 501, 539–542. doi: 10.1038/nature12529

Tóth, M., Móra, A., Kiss, B., Dévai, G., and Specziár, A. (2012). Are macrophyte-dwelling Chironomidae (Diptera) largely opportunistic in selecting plant species? *Eur. J. Entomol.* 109, 247–260. doi: 10.14411/eje.2012.033

USEPA (2012). *Freshwater Biological Traits Database (EPA/600/R-11/038F). Environmental Protection Agency*. Washington, DC: Washington univercity.

Vallenduuk, H. J., and Moller Pillot, H. K. M. (2007). *Chironomidae Larvae of the Netherlands and Adjacent Lowlands. General ecology and Tanypodinae*. Zeist: KNNV Publishing.

Velichkevich, F. Y., and Zastawniak, E. (2006). *Atlas of Pleistocene vascular plant macroremains of Central and Eastern Europe, Part I – Pteridophytes and monocotyledons. W*. Cracow: Polish Academy of Sciences.

Velichkevich, F. Y., and Zastawniak, E. (2008). *Atlas of vascular plant macroremains from the Pleistocene of central and eastern Europe, Part II – Herbaceous dicotyledons. W*. Poland: Szafer Institute of Botany.

Vogt, R. J., Beisner, B. E., and Prairie, Y. T. (2010). Functional diversity is positively associated with biomass for lake diatoms. *Freshwater Biol.* 55, 1636–1646.

Wachecka-Kotkowska, L. (2004a). Ewolucja doliny Luciąży – uwarunkowania klimatyczne a lokalne. *Acta Geogr. Lodziensia* 86, 1–161.

Wachecka-Kotkowska, L. (2004b). Zmiany środowiska doliny dolnej Luciąży w holocenie. Acta Universitatis Lodziensis. *Folia Geogr. Phys.* 6, 47–70.

Walker, I. R. (2001). "Chironomids: Chironomidae and related Diptera," in *Tracking environmental change using lake sediments, Volume 4: Zoological Indicators*, eds J. P. Smol, H. J. B. Birks, and W. M. Last (Do: Kluwer Academic Press), 43–66.

Walker, I. R., Fernando, C. H., and Paterson, C. G. (1985). Association of Chironomidae (Diptera) of shallow, acid, humic lakes and bog pools in Atlantic Canada, and a comparison with an earlier paleoecological investigation. *Hydrobiologia* 120, 11–22. doi: 10.1007/bf00034586

Walsh, C., and Mac Nally, R. (2013). *hier.part: Hierarchical Partitioning. R package version 1.0-4*. https://CRAN.R-project.org/package=hier.part.

Wei, T., and Simko, V. (2017). *R package "corrplot": Visualization of a Correlation Matrix (Version 0.84)*. https://guthub.com/taiyun/corrplot.

Wickham, H. (2016). *ggplot 2: Elegant Graphics for Data Analysis*. New York: Springer-Verlag.

Woodward, F. I. (1987). Stomatal numbers are sensitive to increases in CO_2 from pre-industrial levels. *Nature* 327, 617–618. doi: 10.1038/327617a0

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Supplementary information

Supplementary Table 1. Variables for cores analyzed in the study. The data was standardized during analyses. Bolded variables were included in further analysis.

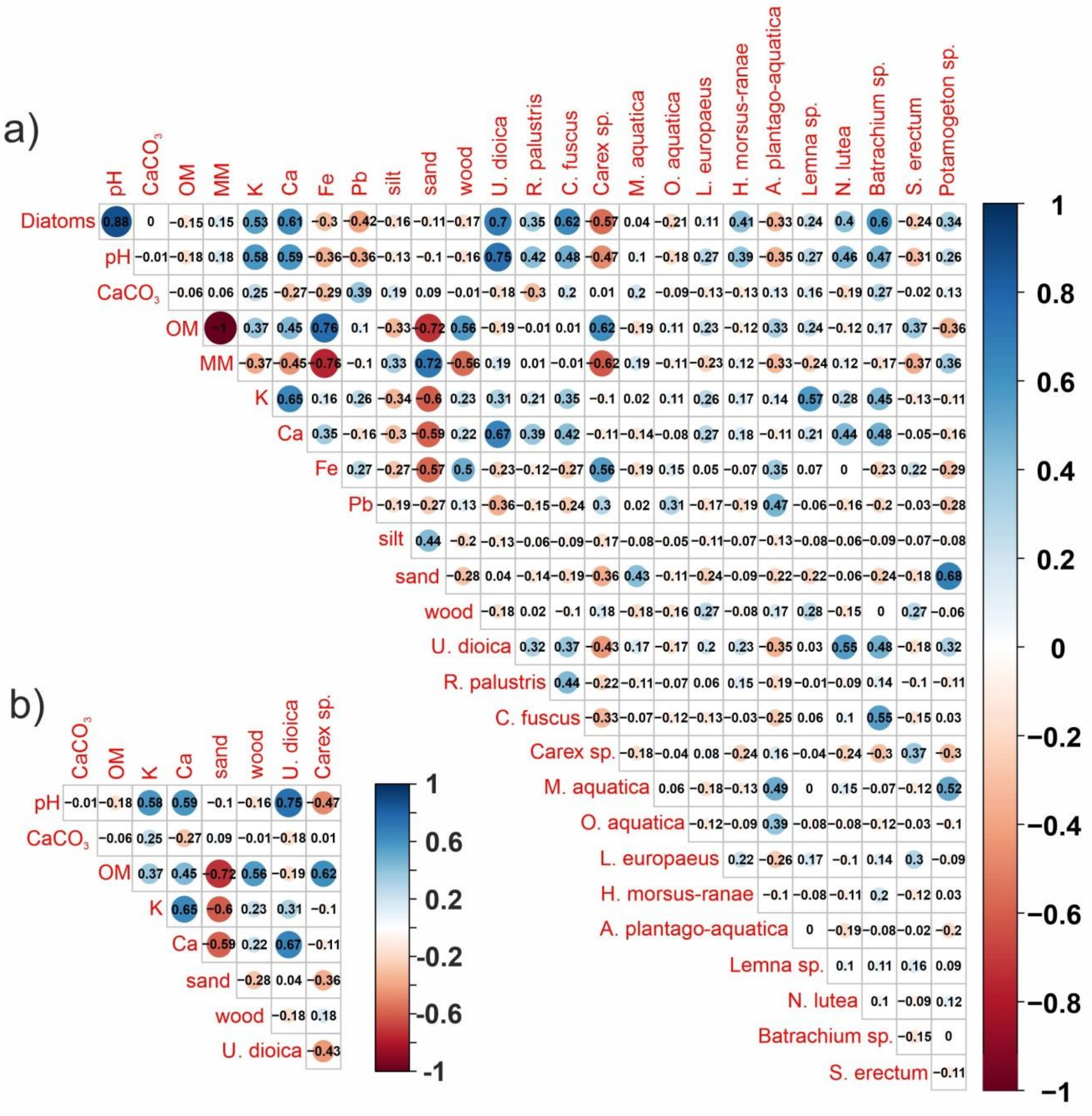
Variable	Code
Diatom concentration [ind./cm^3]	Diatoms
pH	**pH**
$CaCO_3$ [%]	**$CaCO_3$**
Organic matter [%]	**OM**
Mineral matter [%]	MM
K [mg/g]	**K**
Ca [mg/g]	Ca
Fe [mg/g]	Fe
Pb [μg/g]	Pb
Silt [%]	silt
Sand [%]	**sand**
Wood [%]	**wood**
***Urtica dioica* [%]**	**U. dioica**
Rorippa palustris [%]	R. palustris
Cyperus fuscus [%]	C. fuscus
***Carex* sp. [%]**	**Carex sp.**
Mentha aquatica [%]	M. aquatica
Oenanthe aquatica [%]	O. aquatica
Lycopus europaeus [%]	L. europaeus
Phragmites australis [%]	P. australis
Hydrocaris morsus-ranae [%]	H. morsus-ranae
Alisma plantago-aquatica [%]	A.plantago-aquatica
Lemna sp.	Lemna sp.
Nuphar lutea [%]	N. lutea
Batrachium sp. [%]	Batrachium sp.
Sparganium erectum [%]	S. erectum
Potamogeton sp. [%]	Potamogeton sp.
Filipendula ulmaria [%]	F. ulmaria

Supplementary Table 2. Most supported (1AIC < 2) models testing for impact of environmental factors on richness of chironomid groups in each typology.

Response variable	**Model**	**df**	**logLik**	**AICc**	**ΔAICc**	**weight**
Tribes/subfamilies richness	pH	3	-45.16	96.9	0.00	0.091
	OM + pH	4	-44.37	97.8	0.86	0.059
	K + OM + pH	5	-43.39	98.4	1.46	0.044
	Carex sp. + pH	4	-44.77	98.6	1.65	0.040
	pH + wood	4	-44.82	98.7	1.75	0.038
	$CaCO_3$ + pH	4	-44.88	98.8	1.88	0.035
	OM + pH + sand	5	-43.65	98.9	1.99	0.034
Mentum types richness	K + OM + pH + wood	6	-58.59	131.5	0.00	0.117
	K + OM + pH	5	-59.96	131.5	0.03	0.116
	K + OM + pH + sand	6	-59.27	132.9	1.37	0.059
	$CaCO_3$ + K + OM + pH + wood	7	-57.86	132.9	1.41	0.058
	$CaCO_3$ + K + OM + pH	6	-59.36	133.0	1.53	0.055
Feeding groups richness	OM + pH + wood	5	-49.47	110.6	0.00	0.098
	K + OM + pH + wood	6	-48.19	110.7	0.16	0.090
	Carex sp. + pH + wood	5	-49.99	111.6	1.06	0.058
	Carex sp. + OM + pH + wood	6	-48.83	112.0	1.43	0.048
	OM + pH + sand + wood	6	-48.99	112.3	1.77	0.040
	OM + pH	4	-51.70	112.5	1.89	0.038
	K + OM + pH + U. dioica + wood	7	-47.66	112.5	1.97	0.037

Supplementary Table 3. Impact of environmental factors used in averaged models on richness of analyzed chironomid groups (generalized linear regression).

Response variable	**Predictor**	**Estimate**	**Adjusted SE**	**Z**	**P**
Tribes/subfamilies richness	Intercept	2.892	0.112	25.8	**<0.001**
	pH	0.799	0.137	5.8	**<0.001**
	OM	0.220	0.168	1.3	0.192
	K	-0.137	0.174	0.8	0.431
	Carex sp.	0.077	0.145	0.5	0.594
	wood	0.086	0.143	0.6	0.547
	$CaCO_3$	0.096	0.118	0.8	0.416
	sand	0.078	0.169	0.460	0.645
	U. dioica	-0.048	0.156	0.3	0.759
Mentum types richness	Intercept	5.244	0.162	32.3	**<0.001**
	pH	1.715	0.227	7.6	**<0.001**
	OM	0.822	0.279	3.0	**0.003**
	K	-0.574	0.257	2.2	**0.025**
	Carex sp.	-0.030	0.234	0.1	0.899
	wood	0.322	0.231	1.4	0.163
	$CaCO_3$	0.180	0.175	1.0	0.303
	sand	0.285	0.267	1.1	0.286
	U. dioica	0.138	0.241	0.6	0.561
Feeding types richness	Intercept	4.222	0.128	33.0	**<0.001**
	pH	0.891	0.173	5.1	**<0.001**
	OM	0.474	0.225	2.1	**0.036**
	K	-0.242	0.208	1.2	0.242
	Carex sp.	0.223	0.184	1.2	0.225
	wood	0.418	0.185	2.3	**0.023**
	$CaCO_3$	0.012	0.139	0.1	0.926
	sand	0.097	0.208	0.5	0.641
	U. dioica	0.143	0.180	0.8	0.426



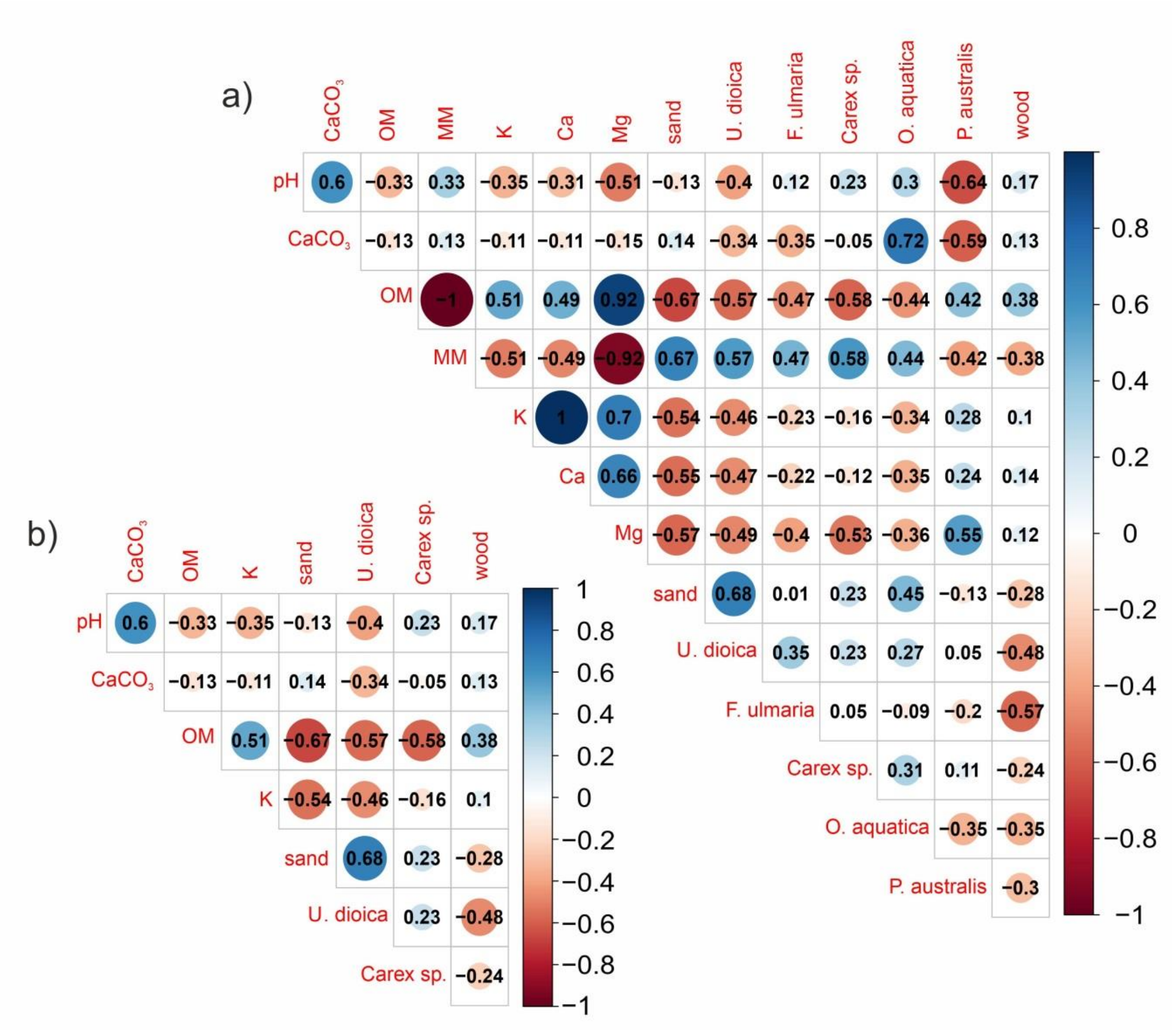
a)

	pH	$CaCO_3$	OM	MM	K	Ca	Fe	Pb	silt	sand	wood	U. dioica	R. palustris	C. fuscus	Carex sp.	M. aquatica	O. aquatica	L. europaeus	H. morsus-ranae	A. plantago-aquatica	Lemna sp.	N. lutea	Batrachium sp.	S. erectum	Potamogeton sp.
Diatoms	0.88	0	−0.15	0.15	0.53	0.61	−0.3	−0.42	−0.16	−0.11	−0.17	0.7	0.35	0.62	−0.57	0.04	−0.21	0.11	0.41	−0.33	0.24	0.4	0.6	−0.24	0.34
pH		−0.01	−0.18	0.18	0.58	0.59	−0.36	−0.36	−0.13	−0.1	−0.16	0.75	0.42	0.48	−0.47	0.1	−0.18	0.27	0.39	−0.35	0.27	0.46	0.47	−0.31	0.26
$CaCO_3$			−0.06	0.06	0.25	−0.27	−0.29	0.39	0.19	0.09	−0.01	−0.18	−0.3	0.2	0.01	0.2	−0.09	−0.13	−0.13	0.13	0.16	−0.19	0.27	−0.02	0.13
OM				−1	0.37	0.45	0.76	0.1	−0.33	−0.72	0.56	−0.19	−0.01	0.01	0.62	−0.19	0.11	0.23	−0.12	0.33	0.24	−0.12	0.17	0.37	−0.36
MM					−0.37	−0.45	−0.76	−0.1	0.33	0.72	−0.56	0.19	0.01	−0.01	−0.62	0.19	−0.11	−0.23	0.12	−0.33	−0.24	0.12	−0.17	−0.37	0.36
K						0.65	0.16	0.26	−0.34	−0.6	0.23	0.31	0.21	0.35	−0.1	0.02	0.11	0.26	0.17	0.14	0.57	0.28	0.45	−0.13	−0.11
Ca							0.35	−0.16	−0.3	−0.59	0.22	0.67	0.39	0.42	−0.11	−0.14	−0.08	0.27	0.18	−0.11	0.21	0.44	0.48	−0.05	−0.16
Fe								0.27	−0.27	−0.57	0.5	−0.23	−0.12	−0.27	0.56	−0.19	0.15	0.05	−0.07	0.35	0.07	0	−0.23	0.22	−0.29
Pb									−0.19	−0.27	0.13	−0.36	−0.15	−0.24	0.3	0.02	0.31	−0.17	−0.19	0.47	−0.06	−0.16	−0.2	−0.03	−0.28
silt										0.44	−0.2	−0.13	−0.06	−0.09	−0.17	−0.08	−0.05	−0.11	−0.07	−0.13	−0.08	−0.06	−0.09	−0.07	−0.08
sand											−0.28	0.04	−0.14	−0.19	−0.36	0.43	−0.11	−0.24	−0.09	−0.22	−0.22	−0.06	−0.24	−0.18	0.68
wood												−0.18	0.02	−0.1	0.18	−0.18	−0.16	0.27	−0.08	0.17	0.28	−0.15	0	0.27	−0.06
U. dioica													0.32	0.37	−0.43	0.17	−0.17	0.2	0.23	−0.35	0.03	0.55	0.48	−0.18	0.32
R. palustris														0.44	−0.22	−0.11	−0.07	0.06	0.15	−0.19	−0.01	−0.09	0.14	−0.1	−0.11
C. fuscus															−0.33	−0.07	−0.12	−0.13	−0.03	−0.25	0.06	0.1	0.55	−0.15	0.03
Carex sp.																−0.18	−0.04	0.08	−0.24	0.16	−0.04	−0.24	−0.3	0.37	−0.3
M. aquatica																	0.06	−0.18	−0.13	0.49	0	0.15	−0.07	−0.12	0.52
O. aquatica																		−0.12	−0.09	0.39	−0.08	−0.08	−0.12	−0.03	−0.1
L. europaeus																			0.22	−0.26	0.17	−0.1	0.14	0.3	−0.09
H. morsus-ranae																				−0.1	−0.08	−0.11	0.2	−0.12	0.03
A. plantago-aquatica																					0	−0.19	−0.08	−0.02	−0.2
Lemna sp.																						0.1	0.11	0.16	0.09
N. lutea																							0.1	−0.09	0.12
Batrachium sp.																								−0.15	0
S. erectum																									−0.11

b)

	$CaCO_3$	OM	K	Ca	sand	wood	U. dioica	Carex sp.
pH	−0.01	−0.18	0.58	0.59	−0.1	−0.16	0.75	−0.47
$CaCO_3$		−0.06	0.25	−0.27	0.09	−0.01	−0.18	0.01
OM			0.37	0.45	−0.72	0.56	−0.19	0.62
K				0.65	−0.6	0.23	0.31	−0.1
Ca					−0.59	0.22	0.67	−0.11
sand						−0.28	0.04	−0.36
wood							−0.18	0.18
U. dioica								−0.43

Supplementary Figure 1. Correlation matrices with Pearson’s r correlation coefficients calculated for the W3(2) core: (A) all predictors and (B) predictors left for further analyses. For full predictor names, see Supplementary Table 1.



Supplementary Figure 2. Correlation matrices with Pearson's r correlation coefficients calculated for the W4 core: (A) all predictors and (B) predictors left for further analyses. For full predictor names, see Supplementary Table 1.

Chapter VII. General discussion

Whereas palaeoecological studies have a long history, only a holistic approach with the use of quantitative tools and multiple proxies gives reliable results (comparable between sites). The findings presented in this thesis confirm the usefulness of subfossil Chironomidae in tracking past local and regional environmental changes. The chironomids are proven to be a valuable proxy in particular when used along other biotic and geochemical analyses, which significantly complement the interpretation of obtained results.

The coring sites selected in the vicinity of the Rozprza stronghold represent both natural (palaeomeander, later oxbow lake) and anthropogenic (moat) small lowland water bodies. Both water bodies were complex ecosystems overgrown with diverse macrophytes and algae, and inhabited by insect (dipteran larvae) and meiocrustacean (cladocerans) communities. However, the investigated processes had a different character in the moat and in the palaeo-oxbow.

The evolution of the oxbow lake recorded in the RP W4 profile happened gradually over thousands of years. After cutting off the river meander in the Early Allerød, the formed oxbow lake existed for over a thousand years (Chapter II). The main drivers of chironomid larvae composition were then large-scale environmental changes, such as climate fluctuations. The only sudden events affecting the lake were flooding episodes. They probably caused the refreshment of the lake with fluvial water and partial destruction of the plant cover. It further inhibited the naturally slow eutrophication process. The terrestrialisation did not happen until mid-Younger Dryas, being a consequence of successive water shallowing (Fig. 11, Chapter II). Similar pattern and duration of natural succession from oxbow to mire was observed elsewhere in the region (e.g. Pawłowski *et al.*, 2015; Kittel *et al.*, 2016; Płóciennik *et al.*, 2020). The studied oxbow in Luciąża River valley fits into the general trend of intensified paludification processes during the transition from Late Glacial to Holocene (Vandenberghe, 2003; Starkel *et al.*, 2013). Nevertheless, such shallow water bodies located in the river floodplains are particularly exposed to the river activity. Unstable conditions could interfere with peat sedentation in the Holocene, leading to periodic recurrence of limnetic conditions within the mire (Kittel *et al.*, 2016; Chapter III). The oxbow studied with RP W4 profile in Rozprza during most of the Holocene had presumably the character of a backswamp throughout most of the Holocene, as suggested by the domination of hygropetric chironomid taxa. The history of studied paleomeander covers ca. 13,000 years since the lake formation to the final (fully terrestrial) stage of its succession (Chapter III).

A completely different succession pattern was represented by the moat surrounding the Rozprza motte. The high water trophic state reaching even hypertrophy, according to total phosphorus chironomid-inferred reconstruction based on British calibration set was permanent, from establishing of this feature ca. 1330 AD on (Fig. 12, Chapter IV). On the one hand, its small size and shallow, muddy bottom were conducive to water warming and increased productivity. On the other hand, the main accelerator of eutrophication was undoubtedly human activity. The inhabitants of the stronghold were most probably affecting moat water directly by supplying it with organic waste. The cultural eutrophication was also enhanced by pastoral and arable farming activities. The crucial nutrients coming from animal husbandry were phosphorus and nitrogen (Carpenter *et al.,* 1998; Taylor *et al.,* 2017). They were accumulating in the catchment and running off to the moat. Such a high enrichment in nutrients led to the fast overgrowing of moat with macrophytes and phytoplankton. The algae likely caused seasonal blooms, which can be harmful for many living organisms (Brodersen & Quinlan, 2006). The negative implications of the eutrophic water conditions (such as pathogenic microorganisms and nuisant insects development) were probably one of the reasons for digging the artificial channel linking the moat with the Luciąża river (Chapter IV). This solution was effective to some extent – after initial decrease of total phosphorus content, the water trophic state increased again (Fig. 12, Chapter IV).

The moat paludification started with peat sedentation after the stronghold was abandoned in the 16th century AD, ca. 150 years since its establishment (Fig. 6, Chapter V). This process, however, did not happen simultaneously in the whole water body. The aquatic ecosystem functioned continuously only in its deepest southern/south-western part (RP W3 cores). The north-eastern part of the moat (RP W1 core) was generally inhabited by less abundant aquatic communities. Chironomidae taxa recorded there had mostly wide ecological preferences, although many of them were associated with macrophytes (Chapter V). Considering the above with lithological and geochemical results, we can conclude that the north-eastern part of the moat was supplied with water mostly during the periodic inflow from the artificial channel. For most of the moat's existence, it probably was a marshy, telmatic habitat with peat deposits and shallow puddles of water (Chapter V). The environmental history of the moat finally ended in the 18th or 19th century AD, with deposition of overbank alluvia (Chapter IV, V).

The activity of nearby river affected studied water bodies and their biotic components in various ways. The natural processes, such as floods and surface runoff could have been accompanied by human-induced rinsing of the moat directly and intentionally with riverine water. These fluvial activities caused changes in the sediment composition by soil erosion, geochemical denudation, inwash of overbank mineral matter and increase of inorganic components (such as SiO_{2ter} and lithophile elements) content (Chapters II, IV, V). The irregular inwash of sand and gravels was reflected in Chironomidae taxa associated with mineral bottom (mainly Tanytarsini). The significant presence of rheophilic midge larvae both in the oxbow (RP W4 core) and the moat deposits were even more evident signals of the river's activity. Besides indicative chironomids (such as *Rheocricotopus*, *Rheotanytarsus* and *Potthastia*), the useful subfossils included Simuliidae larvae head capsules. These truly rheophilic dipterans were recorded both in the Late Glacial and Holocene part of the oxbow/backswamp (Chapters II, III), as well as throughout the main moat (cores RP W1, RP W3 (2) and RP W3(4)). No distinct geochemical evidence indicates large-scale floods during the late medieval human settlement in the stronghold. Therefore, the biota associated with lotic conditions were probably washed into the moat with Luciąża River water through the artificial channel (Chapter IV).

The flooding episodes were in turn the main cause of periodic water level increase in the oxbow lake (and later the backswamp) over its long history, as inferred from the RP W4 core. They were recognised mainly using geochemical indicators, rheophilic midges and increased frequency of planktonic Cladocera. The main floods in Luciąża River valley during Late Glacial happened probably ca. 13,100-13,000 cal. BP and ca. 12,800-12,500 cal. BP (Chapter II). They coincide with global climatic changes, which were likely the main driver of hydrological fluctuations (Starkel *et al.*, 2013; Dzieduszyńska *et al.*, 2014). In the period of peat sedentation during the oxbow terrestrialisation in the Holocene a few episodes of higher water level, when chironomid assemblages could have developed, were recorded. The first Holocene (Atlantic) chironomid assemblage can be linked to the existence of shallow water body because the terrestrialisation process was already in progress, as suggested by the domination of hygropetric and eurytopic taxa. *Stempelinella-Zavrelia and Corynoneura arctica* morphotypes classified here as rheophiles are not exclusively associated with lotic habitats (Giłka, 2011; Moller Pillot, 2013) and cannot be treated as the indicators of the water flow in this case. However, the second limnetic episode of the backswamp in the Early Middle Ages was very likely the effect of hydrological fluctuations in the Early Medieval Period (from 6th century AD). The continental climate with distinct cooling led to frequent anomalies, such as droughts and floods (Büntgen *et al.*, 2011). The trace of the latter is recorded in head capsules of rheophilic chironomids, such as *Rheocricotopus effusus*-type (Fig. 3.1, Chapter III).

Chironomidae subfossils from the oxbow lake deposits (RP W4 core) were also used to track palaeoclimatic fluctuations in central Poland (Chapter II). The summer air temperature, however, could only be estimated for the Late Glacial part of the sequence, as the Holocene backswamp was inhabited by too scarce chironomid assemblages for quantitative reconstruction. All models used show similar trends. The Allerød interstadial was relatively cool in comparison to warm summers at the onset of Younger Dryas (up to 15-16 °C) (Fig. 11, Chapter II). Such high temperatures in this well-documented ‘cold event’ seem to stand in contrast to the general findings (Carlson, 2010). However, the Chironomidae assemblages are used to reconstruct the mean air temperature of the warmest month (July). As the Younger Dryas is known for the increase of continentality (Schenk *et al.,* 2018), it cannot be ruled out, that the summers could have been as warm as in modern Russia (The World Bank Group, 2021). Moreover, this event was more distinct in the northern and western parts of Europe (Brooks & Langdon, 2014), and reconstructions from central-eastern part of the continent often give similar results to those from Rozprza (Kubovčík *et al.*, 2021).

Another inference from chironomid-based paleotemperature reconstruction is the record of cool inter-Allerød oscillation (corresponding to Gerzensee oscillation; Schwander *et al.*, 2000). Although some research from Poland suggested it earlier, this is the first quantitative record of this event from East-Central Europe obtained by such high-resolution analysis.

The Chironomidae assemblages from lake sediments are very good palaeoindicators of the past climate changes. Besides natural succession towards telmatic/semiterrestrial habitats, the shifts in the taxonomic composition were mostly induced by summer air temperature fluctuations, and during the fully limnetic phase (Late Glacial up to mid-Younger Dryas) it was the main factor (Chapter II). The midge subfossils from the moat system, though abundant, could not be used to reconstruct climatic conditions in the Late Medieval and Early Modern periods, as they were primarily driven by the human-induced trophic and habitat changes.

The chironomid larvae abundance and composition in the studied water bodies were shaped by the above-described processes. The highest morphotype richness and abundance of midge subfossils were recorded in the moat profiles RP W3 (Fig. 7.1, Table 1.1). However, most of this richness was constituted by Chironomini tribe representatives. Chironomini larvae mostly live in soft sediments, such as silt and mud. Many of them prefer eutrophic water and can survive oxygen deficiencies (Moller Pillot, 2009). The fresh water supplies and diversity of habitats available enable the occurrence of more demanding (e.g. rheophiles) and phytophilous taxa, such as *Corynoneura arctica*-type. On the other hand, Diamesinae is the subfamily recorded only in the oxbow sediments (Fig. 7.1.).

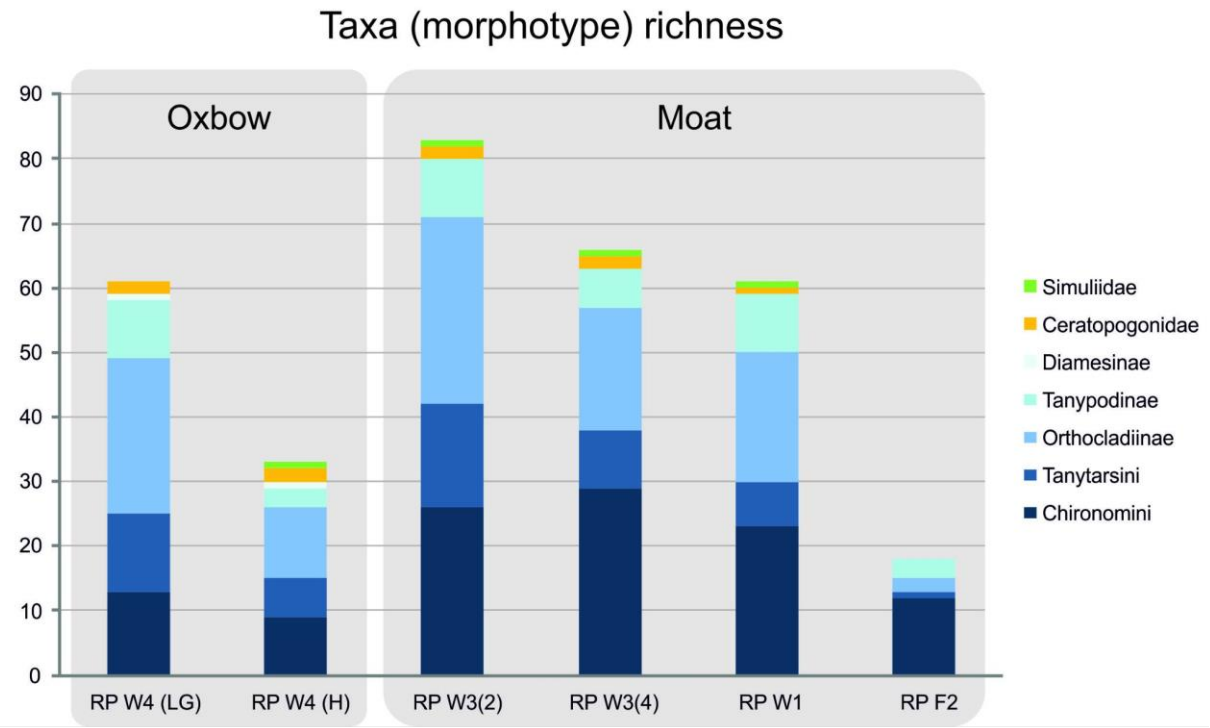


Fig. 7.1. A morphotype richness comparison between studied profiles, regarding main taxonomic divisions.

A relatively high (morpho-)taxonomic Chironomidae richness both in the oxbow and in the main moat is also reflected among functional feeding groups (FFGs). Predators (mainly Tanypodinae) co-occurred with filtrators, collectors, shredders, scrapers and plant-miners (Chapter VI). Such a high diversity among trophic guilds may indicate a complex, well-functioning ecosystem. While the larvae mouthpart shape is (at least partially) associated with feeding preferences (Olafsson, 1992), it was tested for indicative value in tracking habitat changes. Available food sources, directly linked to the habitat substrate structure, vegetation and geochemical conditions, seem to be one of the main drivers in shaping chironomid assemblages. The analyses of profiles derived from both studied water bodies (RP W3(2) and RP W4) revealed that the chironomid composition both on morphological, functional and higher taxonomic levels is shaped by similar (meso-)habitat factors, mainly organic matter content and pH (Fig. 4, Chapter VI). Therefore, a general analysis of Chironomidae larvae based on simplified mouthpart typology can be a tool to obtain some basic, preliminary results on habitat changes.

A comparison of the studied palaeo-oxbow during the Late Vistulian (RP W4) and the deepest part of the moat (RP W3(2)) shows that the habitat changes in the moat were relatively fast, being induced by anthropogenic eutrophication and water acidification after the stronghold was abandoned. The oxbow sequence, though covering a similar timespan, indicates stable conditions, favourable for a functionally diverse ecosystem (Chapter VI). More distinct habitat changes started to happen no sooner than in the Holocene (Chapter III).

Conclusions

This research explored the applicability of subfossil chironomid assemblages in tracking past natural and anthropogenic processes in small water bodies. The hypotheses were tested on the basis of the sediment profiles from palaeo-oxbow and medieval stronghold's moat in the Łódź region (central Poland).

The research revealed that artificial features, such as moats, were impacted by the same environmental processes, as those in comparable natural water bodies. All aquatic ecosystems underwent a similar succession pattern with increasing trophic state, through fen/mire towards fully terrestrial environment. The paludification of the moat happened much faster in comparison to the oxbow lake, being accelerated by the human-induced eutrophication (**H1 confirmed**). The stronghold inhabitants had a great impact on the moat ecosystem. They not only supplied the water with nutrients from household and farming activities, but also probably refreshed it using the artificial channel from the Luciąża River (**H2 confirmed**). Moreover, the ecofacts (wood, stems etc.) and artefacts (e.g. pottery) could serve as additional habitats for aquatic plants and animals, including chironomid larvae. Such point features, but also depth differences and other morphological parameters influenced the range and scale of processes shaping habitat composition. The habitat-dependent Chironomidae assemblages differed throughout the moat, which **confirms the third hypothesis**.

The results of the RP W4 core analysis indicate that Chironomidae assemblages in oxbow lakes are shaped mainly by long-term climate changes. The global summer air temperature fluctuations directly influence stenothermic chironomids. It also causes, however, changes in precipitation and river activity, macrophyte cover, trophic state and paludification. Such changes affect other ecologically sensitive groups of chironomids, being indirectly driven by global (rarely regional or local) climatic changes. In contrast, the midge community composition in a moat was determined mainly by local (even point) habitat-scale factors, which **confirms the fourth hypothesis**.

This PhD research presents the first application of subfossil Chironomidae analysis in the palaeoecological study of historical moat deposits. The research contributes to expanding knowledge about the ecology of such anthropogenic water bodies, commonly used in the Middle Ages and the Early Modern Period. It examines past ecosystems as holistically as possible, using a spatial approach and multiple proxies. Within the PhD project, a novel trait-based classification of

Chironomidae was tested as a tool for interpretation of palaeoecological midge data, giving promising results for future studies. Finally, it provides the high-resolution reconstruction of palaeoclimate in the Luciąża River valley during the Late Glacial. Chironomid-inferred summer air palaeotemperatures confirm the short, cool inter-Allerød oscillation in central Poland. The results bring new information on the regional character of global climatic events, such as Younger Dryas, and hydrological changes associated with them.

To sum up, the opportunity to track changes in the midge communities both in natural and anthropogenic water bodies in the same area was used. It examined the relation between biotic components and their abiotic environment, indicating the ecosystem response to the climate and landscape changes, as well as disturbances caused by the local factors. The research proved the high potential of subfossil Chironomidae remains in the reconstruction of eutrophication, paludification, fluvial processes, habitat changes and climatic fluctuations. The ecological diversity of these insects is of great value, and it provides many areas for further studies.

References

Brodersen K.P., Quinlan R. 2006. Midges as palaeoindicators of lake productivity, eutrophication and hypolimnetic oxygen. Quaternary Science Reviews 25, 1995–2012.

Brooks S.J., Langdon P.G. 2014. Summer temperature gradients in northwest Europe during the Lateglacial to early Holocene transition (15-8 ka BP) inferred from chironomid assemblages. Quaternary International 341, 80–90.

Brooks S. J., Bennion H., Birks H. J. B. 2001. Tracing lake trophic history with a chironomid-total phosphorus inference model. Freshwater Biology 46 (4), 513–533.

Büntgen U., Tegel W., Nicolussi K., McCormick M., Frank D., Trouet V., Kaplan J.O., Herzig F., Heussner K.U., Wanner H., Luterbacher J., Esper J. 2011. 2500 years of European climate variability and human susceptibility. Science 331, 578–582.

Carlson A.E. 2010. What caused the younger Dryas cold event? Geology 38 (4), 383–384.

Carpenter S.R., Caraco N.F., Correll D.L., Howarth R.W., Sharpley A.N., Smith V.H. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8, 559–568.

Dzieduszyńska D.A. 2019. Timing of environmental changes of the Weichselian decline (18.0–11.5 ka cal BP) using frequency distribution of 14C dates for the Łódź region, Central Poland. Quaternary International 501, 135–146.

Dzieduszyńska D.A., Kittel P., Petera-Zganiacz J., Brooks S.J., Korzeń K., Krąpiec M., Pawłowski D., Płaza D.K., Płóciennik M., Stachowicz-Rybka R., Twardy J. 2014. Environmental influence on forest development and decline in the Warta River valley (Central Poland) during the Late Weichselian. Quaternary International 324, 99–114.

Giłka W. 2011. Analiza różnorodności faunistycznej ochotkowatych z plemienia Tanytarsini w Europie (Diptera: Chironomidae). Dipteron, Bulletin of the Dipterological Section of the Polish Entomological Society 27, 11–31.

Kittel P., Płóciennik M., Borówka R.K., Okupny D., Pawłowski D., Peyron O., Stachowicz-Rybka R., Obremska M., Cywa K. 2016. Early Holocene hydrology and environments of the Ner River (Poland). Quaternary Research 85 (2), 187–203.

Kubovčík V., Hošek J., Heiri O., Rojik F., Vaterková S., Trubač J., Pokorný P. 2021. Chironomid-based temperature and environmental reconstructions of the last glacial termination in southern Bohemia, Czech Republic. Palaeogeography, Palaeoclimatology, Palaeoecology 567, 110239.

Moller Pillot H. K. M. 2013. Chironomidae larvae of the Netherlands and adjacent lowlands, Biology and Ecology of the aquatic Orthocladiinae, Prodiamesinae, Diamesinae, Buchonomyiinae, Podonominae, Telmatogetoninae. KNNV Publishing, Zeist.

Pawłowski D., Kowalewski G., Milecka K., Płóciennik M., Woszczyk M., Zieliński T., Okupny D., Włodarski W., Forysiak J. 2015. A reconstruction of the palaeohydrological conditions of a floodplain: a multi-proxy study from the Grabia River valley mire, central Poland. Boreas 44, 543–562.

Płóciennik M., Pawłowski D., Vilizzi L., Antczak-Orlewska O. 2020. From oxbow to mire: Chironomidae and Cladocera as habitat palaeoindicators. Hydrobiologia 847, 3257–3275.

Olafsson J. S. 1992. A comparative study on mouthpart morphology of certain larvae of Chironomini (Diptera: Chironomidae) with a reference to the larval feeding habits. Journal of Zoology 228(2), 183–204.

Schenk F., Väliranta M., Muschitiello F., Tarasov L., Heikkilä M., Björck S., Brandefelt J., Johansson A.V., Näslund J.-O., Wohlfarth B. 2018. Warm summers during the Younger Dryas cold reversal. Nature Communications 9, 1634.

Schwander J., Eicher U., Amman B. 2000. Oxygen isotopes of lake marl at Gerzensee and Leysin (Switzerland), covering the Younger Dryas and two minor oscillations, and their correlation to the GRIP ice core. Palaeogeography, Palaeoclimatology, Palaeoecology 159, 203–214.

Starkel L., Michczyńska J.D., Krąpiec M., Margielewski W., Nalepka D., Pazdur A. 2013. Progress in the Holocene chrono-climatostratigraphy of Polish territory. Geochronometria 40, 1–21.

Taylor K.J., Potito A.P., Beilman D.W., Ghilardi B., O'Connell M. 2017. Impact of early prehistoric farming on chironomid communities in northwest Ireland. Journal of Paleolimnology 57, 227–244.

The World Bank Group 2021. Climate Change Knowledge Portal for Development Practitioners and Policy Makers. Available at: https://climateknowledgeportal.worldbank.org/country/russian-federation/climate-data-historical

Vandenberghe J. 2003. Climate forcing of fluvial system development: an evolution of ideas. Quaternary Science Reviews 22, 2053–2060.

Contribution statements

mgr Olga Antczak-Orlewska Łódź, 13.05.2022
Katedra Zoologii Bezkręgowców i Hydrobiologii
Wydział Biologii i Ochrony Środowiska
Uniwersytet Łódzki

OŚWIADCZENIE

1. Oświadczam, że w pracy:

   Antczak-Orlewska O., Okupny D., Pawłowski D., Kotrys B., Krąpiec M., Luoto T.P., Peyron O., Płóciennik M., Stachowicz-Rybka R., Wacnik A., Szmańda J.B., Szychowska-Krąpiec E., Kittel P. 2021. The environmental history of the oxbow in the Luciąża River valley – Study on the specific microclimate during Allerød and Younger Dryas in central Poland. *Quaternary International* (opublikowana on-line, w druku)

jestem autorem korespondencyjnym. Mój udział polegał na opracowaniu koncepcji i założeń pracy, wykonaniu analizy subfosylnych ochotek (Chironomidae) z późnoglacjalnej części profilu RP W4, wykonaniu analizy DCA, przygotowaniu części rycin i tabel, wiodącej roli w interpretacji uzyskanych wyników oraz przygotowaniu manuskryptu.
Szacuję go na 45 %.

2. Oświadczam, że w pracy:

   Kittel P., Sikora J., **Antczak, O.**, Brooks S.J., Elias S.A., Krąpiec M., Luoto T.P., Okupny D., Pawłowski D., Płóciennik M., Rzodkiewicz M., Stachowicz-Rybka R., Wacnik A. 2018. The palaeoecological development of the Late Medieval moat – Multiproxy research at Rozprza, Central Poland. *Quaternary International* 482, 131-156

mój udział polegał na wykonaniu analiz subfosylnych ochotek (Chironomidae) z profilu RP W3(2), opracowaniu części rycin, interpretacji uzyskanych wyników oraz przygotowaniu manuskryptu.
Szacuję go na 5 %.

3. Oświadczam, że w pracy:

   Antczak-Orlewska O., Okupny D., Kruk A., Bailey R.I., Płóciennik M., Sikora J., Krąpiec M., Kittel P. A closer look into a medieval moat – the temporal and spatial chironomid-based reconstruction of habitat mosaic and ecosystem functioning. *Scientific Reports* (w recenzji)

jestem autorem korespondencyjnym. Mój udział polegał na opracowaniu koncepcji pracy, wykonaniu analiz subfosylnych ochotek (Chironomidae) z czterech profili osadów z fosy, przygotowaniu większości rycin i tabel oraz wiodącej roli w interpretacji uzyskanych wyników i przygotowaniu manuskryptu.
Szacuję go na 60 %.

4. Oświadczam, że w pracy:

   Antczak-Orlewska O., Płóciennik M., Sobczyk R., Okupny D., Stachowicz-Rybka R., Rzodkiewicz M., Siciński J., Mroczkowska A., Krąpiec M., Słowiński M., Kittel P. 2021. Chironomidae morphological types and functional feeding groups as a habitat complexity vestige. *Frontiers in Ecology and Evolution* 8, 583831

jestem autorem korespondencyjnym. Mój udział polegał na opracowaniu koncepcji i założeń pracy, wykonaniu analiz subfosylnych ochotek (Chironomidae), interpretacji uzyskanych wyników, przygotowaniu rycin i tabel oraz wiodącej roli w przygotowaniu manuskryptu.
Szacuję go na 50 %.

Olga Antczak-Orlewska

dr Mateusz Płóciennik
Katedra Zoologii Bezkręgowców i Hydrobiologii
Wydział Biologii i Ochrony Środowiska
Uniwersytet Łódzki

Łódź, 13.05.2022

OŚWIADCZENIE

1. Oświadczam, że w pracy:

   Antczak-Orlewska O., Okupny D., Pawłowski D., Kotrys B., Krąpiec M., Luoto T.P., Peyron O., Płóciennik M., Stachowicz-Rybka R., Wacnik A., Szmańda J.B., Szychowska-Krąpiec E., Kittel P. 2021. The environmental history of the oxbow in the Luciąża River valley – Study on the specific microclimate during Allerød and Younger Dryas in central Poland. *Quaternary International* (opublikowana on-line, w druku)

mój wkład polegał na udziale w opracowywaniu koncepcji pracy, udziale w interpretacji uzyskanych wyników oraz w przygotowaniu manuskryptu.
Szacuję go na 7 %.

2. Oświadczam, że w pracy:

   Kittel P., Sikora J., Antczak, O., Brooks S.J., Elias S.A., Krąpiec M., Luoto T.P., Okupny D., Pawłowski D., Płóciennik M., Rzodkiewicz M., Stachowicz-Rybka R., Wacnik A. 2018. The palaeoecological development of the Late Medieval moat – Multiproxy research at Rozprza, Central Poland. *Quaternary International* 482, 131-156

mój wkład polegał na weryfikacji oznaczeń szczątków Chironomidae, analizie DCA, udziale w interpretacji uzyskanych wyników oraz w przygotowaniu manuskryptu.
Szacuję go na 5 %.

3. Oświadczam, że w pracy:

   Antczak-Orlewska O., Okupny D., Kruk A., Bailey R.I., Płóciennik M., Sikora J., Krąpiec M., Kittel P. A closer look into a medieval moat – the temporal and spatial chironomid-based reconstruction of habitat mosaic and ecosystem functioning. *Scientific Reports* (w recenzji)

mój wkład polegał na udziale w opracowaniu koncepcji pracy, wykonaniu analizy CCA, udziale w interpretacji uzyskanych wyników oraz w przygotowaniu manuskryptu.
Szacuję go na 11 %.

4. Oświadczam, że w pracy:

   Antczak-Orlewska O., Płóciennik M., Sobczyk R., Okupny D., Stachowicz-Rybka R., Rzodkiewicz M., Siciński J., Mroczkowska A., Krąpiec M., Słowiński M., Kittel P. 2021. Chironomidae morphological types and functional feeding groups as a habitat complexity vestige. *Frontiers in Ecology and Evolution* 8, 583831

mój wkład polegał na udziale w opracowaniu koncepcji pracy i interpretacji uzyskanych wyników oraz udziale w przygotowaniu manuskryptu.
Szacuję go na 21 %.

....

dr hab. Dominik Pawłowski. prof. UAM
Instytut Geologii
Wydział Nauk Geograficznych i Geologicznych
Uniwersytet im. Adama Mickiewicza w Poznaniu

Poznań, 13.05.2022

OŚWIADCZENIE

1. Oświadczam, że w pracy:

   Antczak-Orlewska O., Okupny D., Pawłowski D., Kotrys B., Krąpiec M., Luoto T.P., Peyron O., Płóciennik M., Stachowicz-Rybka R., Wacnik A., Szmańda J.B., Szychowska-Krąpiec E., Kittel P. 2021. The environmental history of the oxbow in the Luciąża River valley – Study on the specific microclimate during Allerød and Younger Dryas in central Poland. *Quaternary International* (opublikowana on-line, w druku)

mój wkład polegał wykonaniu analizy subfosylnych wioślarek (Cladocera) z późnoglacjalnej części profilu RP W4, udziale w interpretacji uzyskanych wyników oraz w przygotowaniu manuskryptu.
Szacuję go na 10 %.

2. Oświadczam, że w pracy:

   Kittel P., Sikora J., Antczak, O., Brooks S.J., Elias S.A., Krąpiec M., Luoto T.P., Okupny D., Pawłowski D., Płóciennik M., Rzodkiewicz M., Stachowicz-Rybka R., Wacnik A. 2018. The palaeoecological development of the Late Medieval moat – Multiproxy research at Rozprza, Central Poland. *Quaternary International* 482, 131-156

mój wkład polegał na wykonaniu analizy subfosylnych wioślarek (Cladocera) z profilu RP W3(2), opracowaniu części rycin, udziale w interpretacji uzyskanych wyników oraz w przygotowaniu manuskryptu.
Szacuję go na 5 %.

prof. dr hab. Piotr Kittel
Katedra Geologii i Geomorfologii
Wydział Nauk Geograficznych
Uniwersytet Łódzki

Łódź, 11.05.2022

OŚWIADCZENIE

1. Oświadczam, że w pracy:

   Antczak-Orlewska O., Okupny D., Pawłowski D., Kotrys B., Krąpiec M., Luoto T.P., Peyron O., Płóciennik M., Stachowicz-Rybka R., Wacnik A., Szmańda J.B., Szychowska-Krąpiec E., Kittel P. 2021. The environmental history of the oxbow in the Luciąża River valley – Study on the specific microclimate during Allerød and Younger Dryas in central Poland. *Quaternary International* (opublikowana on-line, w druku)

mój wkład polegał na nadzorze nad projektem, organizacji prac terenowych, poborze prób, analizie paleogeograficznej, udziale w interpretacji uzyskanych wyników oraz w przygotowaniu manuskryptu. Szacuję go na 9 %.

2. Oświadczam, że w pracy:

   Kittel P., Sikora J., Antczak, O., Brooks S.J., Elias S.A., Krąpiec M., Luoto T.P., Okupny D., Pawłowski D., Płóciennik M., Rzodkiewicz M., Stachowicz-Rybka R., Wacnik A. 2018. The palaeoecological development of the Late Medieval moat – Multiproxy research at Rozprza, Central Poland. *Quaternary International* 482, 131-156

mój wkład polegał na nadzorze nad projektem, organizacji prac terenowych, poborze prób, analizie paleogeograficznej, opracowaniu koncepcji artykułu, udziale w interpretacji uzyskanych wyników oraz w przygotowaniu manuskryptu.
Szacuję go na 25 %.

4. Oświadczam, że w pracy:

Antczak-Orlewska O., Okupny D., Kruk A., Bailey R.I., Płóciennik M., Sikora J., Krąpiec M., Kittel P. A closer look into a medieval moat – the temporal and spatial chironomid-based reconstruction of habitat mosaic and ecosystem functioning. *Scientific Reports* (w recenzji)

mój wkład polegał na nadzorze nad projektem, organizacji prac terenowych, poborze prób, analizie paleogeograficznej, udziale w interpretacji uzyskanych wyników oraz w przygotowaniu manuskryptu.
Szacuję go na 9 %.

5. Oświadczam, że w pracy:

Antczak-Orlewska O., Płóciennik M., Sobczyk R., Okupny D., Stachowicz-Rybka R., Rzodkiewicz M., Siciński J., Mroczkowska A., Krąpiec M., Słowiński M., Kittel P. 2021. Chironomidae morphological types and functional feeding groups as a habitat complexity vestige. *Frontiers in Ecology and Evolution* 8, 583831

mój wkład polegał na organizacji prac terenowych, poborze prób, analizie paleogeograficznej oraz udziale w przygotowaniu manuskryptu.
Szacuję go na 5 %.

....

dr Daniel Okupny
Instytut Nauk o Morzu i Środowisku
Uniwersytet Szczeciński

Szczecin, 13.05.2022

OŚWIADCZENIE

1. Oświadczam, że w pracy:

   Antczak-Orlewska O., Okupny D., Pawłowski D., Kotrys B., Krąpiec M., Luoto T.P., Peyron O., Płóciennik M., Stachowicz-Rybka R., Wacnik A., Szmańda J.B., Szychowska-Krąpiec E., Kittel P. 2021. The environmental history of the oxbow in the Luciąża River valley – Study on the specific microclimate during Allerød and Younger Dryas in central Poland. *Quaternary International* (opublikowana on-line, w druku)

mój wkład polegał wykonaniu analiz geochemicznych osadów z późnoglacjalnej części profilu RP W4, przygotowaniu części rycin, udziale w interpretacji uzyskanych wyników oraz w przygotowaniu manuskryptu.
Szacuję go na 15 %.

2. Oświadczam, że w pracy:

   Kittel P., Sikora J., Antczak, O., Brooks S.J., Elias S.A., Krąpiec M., Luoto T.P., Okupny D., Pawłowski D., Płóciennik M., Rzodkiewicz M., Stachowicz-Rybka R., Wacnik A. 2018. The palaeoecological development of the Late Medieval moat – Multiproxy research at Rozprza, Central Poland. *Quaternary International* 482, 131-156

mój wkład polegał na wykonaniu analiz geochemicznych osadów z profilu RP W3(2), opracowaniu części rycin, udziale w interpretacji uzyskanych wyników oraz w przygotowaniu manuskryptu.
Szacuję go na 5 %.

4. Oświadczam, że w pracy:

   Antczak-Orlewska O., Okupny D., Kruk A., Bailey R.I., Płóciennik M., Sikora J., Krąpiec M., Kittel P. A closer look into a medieval moat – the temporal and spatial chironomid-based reconstruction of habitat mosaic and ecosystem functioning. *Scientific Reports* (w recenzji)

mój wkład polegał na wykonaniu analiz geochemicznych czterech profili osadów z fosy, udziale w interpretacji uzyskanych wyników oraz w przygotowaniu manuskryptu.
Szacuję go na 5 %.

5. Oświadczam, że w pracy:

   Antczak-Orlewska O., Płóciennik M., Sobczyk R., Okupny D., Stachowicz-Rybka R., Rzodkiewicz M., Siciński J., Mroczkowska A., Krąpiec M., Słowiński M., Kittel P. 2021. Chironomidae morphological types and functional feeding groups as a habitat complexity vestige. *Frontiers in Ecology and Evolution* 8, 583831

mój wkład polegał na wykonaniu analiz geochemicznych osadów z profili RP W4 i RP W3(2), udziale w interpretacji uzyskanych wyników oraz w przygotowaniu manuskryptu.
Szacuję go na 5 %.

Daniel Okupny

…………………………………………….

Łódź, 15 maja 2022 r.

prof. dr hab. Andrzej Kruk
Katedra Ekologii i Zoologii Kręgowców
Wydział Biologii i Ochrony Środowiska
Uniwersytet Łódzki

OŚWIADCZENIE

Oświadczam, że w pracy:

> Antczak-Orlewska O., Okupny D., Kruk A., Bailey R.I., Płóciennik M., Sikora J., Krąpiec M., Kittel P.A. closer look into a medieval moat – the temporal and spatial chironomid-based reconstruction of habitat mosaic and ecosystem functioning. *Scientific Reports* (w recenzji)

mój wkład polegał wykonaniu analiz statystycznych przy użyciu metody samoorganizujących się sieci neuronowych (SOM) oraz analizy gatunków wskaźnikowych opartej na IndVal, opracowaniu części rycin oraz udziale w przygotowaniu manuskryptu.

Szacuję go na 5 %.

Andrzej Kruk
....

mgr Robert Sobczyk
Katedra Zoologii Bezkręgowców i Hydrobiologii
Wydział Biologii i Ochrony Środowiska
Uniwersytet Łódzki

Łódź, 13.05.2022

OŚWIADCZENIE

Oświadczam, że w pracy:

Antczak-Orlewska O., Płóciennik M., Sobczyk R., Okupny D., Stachowicz-Rybka R., Rzodkiewicz M., Siciński J., Mroczkowska A., Krąpiec M., Słowiński M., Kittel P. 2021. Chironomidae morphological types and functional feeding groups as a habitat complexity vestige. *Frontiers in Ecology and Evolution* 8, 583831

mój wkład polegał wykonaniu analiz statystycznych, w tym analizy redundancji RDA, ogólnych modeli liniowych (GLM) oraz hierarchicznego partycjonowania (*hierarchical partitioning*), opracowaniu części rycin i tabel oraz udziale w przygotowaniu manuskryptu.

Szacuję go na 7 %.

Robert Sobczyk
....

mgr Olga Antczak-Orlewska Łódź, 1.06.2022
Katedra Zoologii Bezkręgowców i Hydrobiologii
Wydział Biologii i Ochrony Środowiska
Uniwersytet Łódzki

OŚWIADCZENIE

Oświadczam, że wkład wszystkich autorów w publikacje wchodzące w skład rozprawy jest następujący:

1. **The environmental history of the oxbow in the Luciąża River valley – Study on the specific microclimate during Allerød and Younger Dryas in central Poland.** ***Quaternary International*** **(opublikowana on-line, w druku)**

Autor	Udział (%)	Wkład
Antczak-Orlewska Olga	45	opracowanie koncepcji i założeń pracy, analiza Chironomidae, analiza DCA, przygotowanie rycin i tabel, interpretacja wyników, przygotowanie manuskryptu
Okupny Daniel	15	analiza geochemiczna, przygotowanie części rycin, udział w interpretacji wyników oraz przygotowaniu manuskryptu
Pawłowski Dominik	10	analiza Cladocera, przygotowanie części rycin, udział w interpretacji wyników oraz przygotowaniu manuskryptu
Kotrys Bartosz	1	rekonstrukcja paleotemperatur na podstawie dostarczonych danych Chironomidae
Krąpiec Marek	1	datowanie radiowęglowe
Luoto Tomi P.	1	rekonstrukcja paleotemperatur na podstawie dostarczonych danych Chironomidae
Peyron Odile	1	rekonstrukcja paleoklimatu na podstawie danych palinologicznych
Płóciennik Mateusz	7	udział w opracowywaniu koncepcji pracy, interpretacji wyników oraz w przygotowaniu manuskryptu
Stachowicz-Rybka Renata	4	analiza makroszczątków roślinnych, przygotowanie części rycin, udział w interpretacji wyników oraz przygotowaniu manuskryptu
Agnieszka Wacnik	4	analiza palinologiczna, przygotowanie części rycin, udział w interpretacji wyników oraz przygotowaniu manuskryptu
Szmańda Jacek B.	1	analiza sedymentologiczna
Szychowska-Krąpiec Elżbieta	1	analiza dendrochronologiczna
Kittel Piotr	9	prace terenowe, analiza paleogeograficzna, przygotowanie części rycin, udział w interpretacji wyników oraz przygotowaniu manuskryptu

2. **The palaeoecological development of the Late Medieval moat – Multiproxy research at Rozprza, Central Poland.** ***Quaternary International*** **482, 131-156**

Autor	Udział (%)	Wkład
Kittel Piotr	25	nadzór nad projektem, prace terenowe, analiza paleogeograficzna, opracowanie koncepcji artykułu, części rycin i tabel, udział w interpretacji wyników i przygotowaniu manuskryptu
Sikora Jerzy	20	prace terenowe, analiza archeologiczna, opracowanie ryciny, udział w interpretacji wyników i przygotowaniu manuskryptu
Antczak Olga	5	analiza Chironomidae, przygotowanie części rycin i tabel, udział w interpretacji wyników i przygotowaniu manuskryptu
Brooks Stephen J.	5	rekonstrukcja stanu troficznego wody na podstawie dostarczonych danych Chironomidae
Elias Scott A.	5	analiza Coleoptera, udział w przygotowaniu manuskryptu
Krąpiec Marek	5	datowanie radiowęglowe
Luoto Tomi P.	5	rekonstrukcja stanu troficznego wody na podstawie dostarczonych danych Chironomidae
Okupny Daniel	5	analiza geochemiczna, przygotowanie części rycin, udział w interpretacji wyników i przygotowaniu manuskryptu
Pawłowski Dominik	5	analiza Cladocera, przygotowanie ryciny, udział w interpretacji wyników i przygotowaniu manuskryptu
Płóciennik Mateusz	5	analiza DCA, weryfikacja oznaczeń Chrironomidae, udział w interpretacji wyników
Rzodkiewicz Monika	5	analiza okrzemek, przygotowanie ryciny, udział w interpretacji wyników i przygotowaniu manuskryptu
Stachowicz-Rybka Renata	5	analiza makroszczątków roślinnych, przygotowanie ryciny, udział w interpretacji wyników i przygotowaniu manuskryptu
Agnieszka Wacnik	5	analiza palinologiczna, przygotowanie ryciny, udział w interpretacji wyników i przygotowaniu manuskryptu

3. **A closer look into a medieval moat – the temporal and spatial chironomid-based reconstruction of habitat mosaic and ecosystem functioning.** ***Scientific Reports*** **(w recenzji)**

Autor	Udział (%)	Wkład
Antczak-Orlewska Olga	60	opracowanie koncepcji i założeń pracy, analiza Chironomidae, przygotowanie rycin i tabel, interpretacja wyników, przygotowanie manuskryptu
Okupny Daniel	5	analiza geochemiczna, przygotowanie części rycin, udział w interpretacji wyników oraz w przygotowaniu manuskryptu
Płóciennik Mateusz	11	udział w opracowaniu koncepcji pracy, interpretacji wyników i przygotowaniu manuskryptu, analiza CCA

Kruk Andrzej	5	analizy SOM i IndVal, udział w przygotowaniu manuskryptu
Bailey Richard I.	5	analiza GLM, udział w przygotowaniu manuskryptu
Sikora Jerzy	4	prace terenowe, analiza archeologiczna, opracowanie modelu DEM i ryciny, udział w interpretacji wyników i w przygotowaniu manuskryptu
Krąpiec Marek	1	datowanie radiowęglowe
Kittel Piotr	9	prace terenowe, analiza paleogeograficzna, udział w interpretacji wyników oraz przygotowaniu manuskryptu

4. **Chironomidae morphological types and functional feeding groups as a habitat complexity vestige. *Frontiers in Ecology and Evolution* 8, 583831**

Autor	Udział (%)	Wkład
Antczak-Orlewska Olga	50	opracowanie koncepcji i założeń pracy, analiza Chironomidae, przygotowanie rycin i tabel, interpretacja wyników, przygotowanie manuskryptu
Płóciennik Mateusz	21	udział w opracowaniu koncepcji pracy, interpretacji wyników oraz w przygotowaniu manuskryptu
Sobczyk Robert	7	analizy statystyczne, opracowanie części rycin i tabel, udział w przygotowaniu manuskryptu
Okupny Daniel	5	analiza geochemiczna, udział w interpretacji wyników oraz w przygotowaniu manuskryptu
Stachowicz-Rybka Renata	3	analiza makroszczątków roślinnych, udział w przygotowaniu manuskryptu
Rzodkiewicz Monika	1	analiza okrzemek
Siciński Jacek	5	udział w przygotowaniu manuskryptu
Mroczkowska Agnieszka	1	udział w przygotowaniu manuskryptu
Krąpiec Marek	1	datowanie radiowęglowe
Słowiński Michał	1	udział w przygotowaniu manuskryptu
Kittel Piotr	5	prace terenowe, analiza paleogeograficzna, udział w przygotowaniu manuskryptu

Olga Antczak-Orlewska

Łódź, dn. 6.VI.2022 r.

Poświadczam zgodność ze stanem faktycznym:

J. Siciński

promotor