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A multi-proxy reconstruction from Lutomiersk–Koziówki, Central Poland, in the context of early modern hemp and flax processing

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ABSTRACT

During an archaeological investigation at Lutomiersk–Koziówki in central Poland, deposits indicative of an old rettery from the 16th–17th century AD were discovered. The artifacts found in the lacustrine deposits, together with historical sources and radiocarbon dates of organic matter, show that the pond at a local mill was present from ca. AD 1525 to at least AD 1620. The high content of *Cannabis* and *Linum* subfossil macro- and micro-remains in the sediment indicate that the pond was most probably used as a rettery for hemp and flax fibre production. Pollen analysis revealed strong deforestation of the local landscape at the beginning of the pond history. Despite high pollution caused by plant retting, species-rich chironomid, cladoceran and diatom communities occupied the pond. Our investigations reveal that the rettery was situated on the artificial channel of a local stream. High abundance of yellow flatsedge (*Cyperus flavescens*) fruit remains and coprophile beetle subfossils indicate that pond was also used as a watering place for cattle. Decline in the concentration of aquatic invertebrate subfossils, diatoms, aquatic and cultivated plant macrofossils, reveals rapid abandonment of the rettery in the mid-17th century AD. For some time after the basin was a telmatic ecosystem overgrown by sedges and bulrush. The basin was finally filled by a high-energy overbank deposition not later than in the beginning of 19th century AD.

1. Introduction

Over the last century the rural landscape in Europe has changed significantly. Small artificial and industrial pools, such as mill ponds, became important refuges for freshwater and wetland biota. Many of them have a long history, dating back to the early modern period (Wood and Barker, 2000; Wood et al., 2001). Some of the natural ponds have been used for flax retting, watering and washing livestock for a long time (Van Dam and Buskens, 1993). Palaeoarchives provide information on how small artificial aquatic systems functioned in the past. Archaeological investigation using multi-proxy palaeoenvironmental data can provide a detailed reconstruction of industrial impacts and ecological functioning of these water bodies.

Until now there have been no records of artificial ponds used as a rettery during the modern period (i.e. after ca. AD 1500) in Poland. Palaeobotanical studies of water basins used for hemp or flax

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retting are not common. Usually this type of human economic activity has been recognized on the basis of palynological studies of bottom deposits from small lakes (e.g. Szczepanek, 1971; Latałowa, 1992; Nakagawa et al., 2000; Schofield and Waller, 2005) and sometimes from medium sized basins (e.g. Mercuri et al., 2002; Wacnik et al., 2012, 2014). Hemp and flax were widely cultivated in northern Europe since the Early Middle Ages. Both taxa were basic materials for every household use in the early modern period. Flax was used for spinning cloth. Flax production in Poland increased from the end of the 14th century AD and surpluses were exported mainly to Flanders, England and Sweden. Hemp was commonly used for string, rope and linen production (Mączak, 1981).

Cottage technologies to produce linen and other materials (Ejstrud, 2011) need special pools for retting, i.e. soaking the fibres in natural or artificial ponds. Most of these pools were transformed or buried after abandonment. During an archaeological investigation at Lutomiersk–Koziówki in Central Poland, rettery relics were recovered. These have been dated on the basis of archaeological evidence. Artifacts found in these the deposits date to the 16th–17th century AD (Kittel et al., 2012).

Our research in Lutomiersk–Koziówki is the first detailed analysis of palaeoecology and human impact in the modern period in the Ner River valley. Until now only prehistoric research on the area has been published (Kittel et al., 2011; Kittel, 2012a, 2014). Late Holocene changes in vegetation in Central Poland are well recognized. The reference palynological sequence for this area, obtained from the Żabieniec peat bog, shows an increasingly open landscape through the late medieval and modern periods, as a result of extensive woodland clearance and transformation to cultivated fields and meadows (Lamentowicz et al., 2009; Balwierz, 2010). Palaeolimnological studies on invertebrates in Poland have usually focused on natural habitats and rarely on artificial water bodies.

Diatoms are frequently used in archaeological contexts as they may provide valuable information on environmental conditions such as salinity, trophic level, pH and depth of water bodies (e.g. Dörfler et al., 2009a,b; Bathurst et al., 2010; Van Landingham, 2010; Hildebrandt-Radke et al., 2011a,b).

Ruiz et al. (2006) and Gathorne-Hardy et al. (2007) showed that Chironomidae are good indicators of the impacts of past human settlement and can be used to reconstruct total phosphorus in archaeological investigations. Analysis of subfossil Cladocera also allows for a detailed reconstruction of eutrophication (Szeroczyńska, 1998a) as well as ecological and hydrological changes (Korhola and Rautio, 2001). Beetle and terrestrial insect subfossils have long been used in archaeological studies and provide information on climate, habitats and cultural activity (e.g. agriculture, cattle farming, hygiene) (Smith et al., 1999; Coope and Elias, 2000; O'Brien et al., 2005).

The researched basin is located in the Ner River valley and is influenced by fluvial activity. Our study investigates the geological, geochemical and palaeoecological conditions of the rettery. Geological and geochemical analyses provide information on geomorphological processes in the depositional basin and in the surrounding catchment. Archaeological and written sources have been used to provide a chronological framework for the history of human activity in the area during modern period.

2. Study area

The Lutomiersk–Koziówki site (51°45′14.7″ N, 19°13′28″ E, 153.5 m a.s.l.) is located in Central Poland (Fig. 1A) in the north western part of Łódź region (Turkowska, 2006) ca. 10 km west of Łódź on the Łask Plateau (Kondracki, 2002). It is situated near Lutomiersk in the Ner River valley (tributary of Warta River), in the vicinity of the mouth of the Zalewka (Wrząca) River.

The archaeological site is situated on a residual hillock of the Weichselian (Vistulian) Ner River terrace (Fig. 1B). The river terrace is composed of sands that accumulated during the Pleniglacial Period of the Weichselian Glaciation (Plenivistulian) as established by thermoluminescence (TL) dating (Kittel, 2012a,b). On the north-western side, the hillock is bounded by a large-scale palaeochannel filled by organic deposits, sands and silts from floods. The palaeochannel began to fill in the late Weichselian and continued in the early and middle Holocene as documented by pollen analysis and radiocarbon (^{14}C) dates on the palaeochannel fills – 9030 ± 160 conv. BP (MKL-284), *i.e.* cal. BC 8631–7713 (2δ range) (Kittel, 2012a,b).

On the eastern side the hillock is limited by the Zalewka River valley floor, and on the western side by the valley floor of the second branch of the stream which is of artificial origin. On the southern side, an artificial channel was established in the modern period (Kittel, 2012a). The remains of a rettery have been uncovered in the north-western part of the archaeological site Lutomiersk–Koziówki No. 3a–c, on the border of the large palaeomeander.

Poland is located within a temperate warm transitional climate zone (Okołowicz, 1969). The area is characterized by more continental conditions than the western and northern part of the country and is drier than the northern part. Climatic conditions in the area are highly variable, caused by the influence of oceanic and continental climate resulting from the transitional character of the area (Kłysik, 2001). The average annual temperature from 1931 to 1989 in the western part of Lodz area is 7.7 °C, the mean temperature of the warmest month (July) is 18 °C and mean temperature of the coldest month (January) is −3.3 °C (Kłysik, 2001). Average annual precipitation from 1951 to 1989 was 590 mm, but varied between 438 and 937 mm (http://www.tutiempo.net).

3. Archaeological and historical background

3.1. Archaeological background

Dozens of important archaeological sites dated to prehistoric and historic times have been discovered in the Ner River valley close to Lutomiersk. One of the most interesting is the site Lutomiersk–Koziówki No. 3a–c uncovered in 1945 and examined from 1946 to 2010 (Muzolf, 2012 – see older publications).

At present, an area of 2300 m^2 has been excavated at Lutomiersk–Koziówki No. 3a–c (Fig. 1B). In this unique archaeological site, numerous archaeological remains have been recognized from the 12 basic cultural–chronological horizons from the Late Palaeolithic to the modern period (Muzolf, 2012). More than 3500 artifacts of the modern period have been excavated from the site. These are mainly fragments of potsherds (94%) and fragments of stove tile, building potsherds, glass products, metals and coins. Most modern period artifacts are dated from the end of 17th until the turn of 19th and 20th cent. AD. It is highly probable that excavated artifacts could have been removed as rubbish from the site. The archaeological site locality is mentioned in 16th cent. sources as part of the Koziówki wilderness and was in the possession of the nobility.

The only archaeological feature of the modern period is the relict of a ditch with fragments of stems, wood elements and a sword in the bottom. A cross-section of the ditch was established in 2010 (Muzolf, 2012) in the western part of excavation No. X, located at the border of a large-scale palaeochannel, at the foot of the hillocks (Figs. 1B and 2). The ditch has been cut within the prehistoric slope cover and substratum deposits (Fig. 2, sygn.: 12–16 and 25–26). Prehistoric slope deposits overlie Late Weichselian and

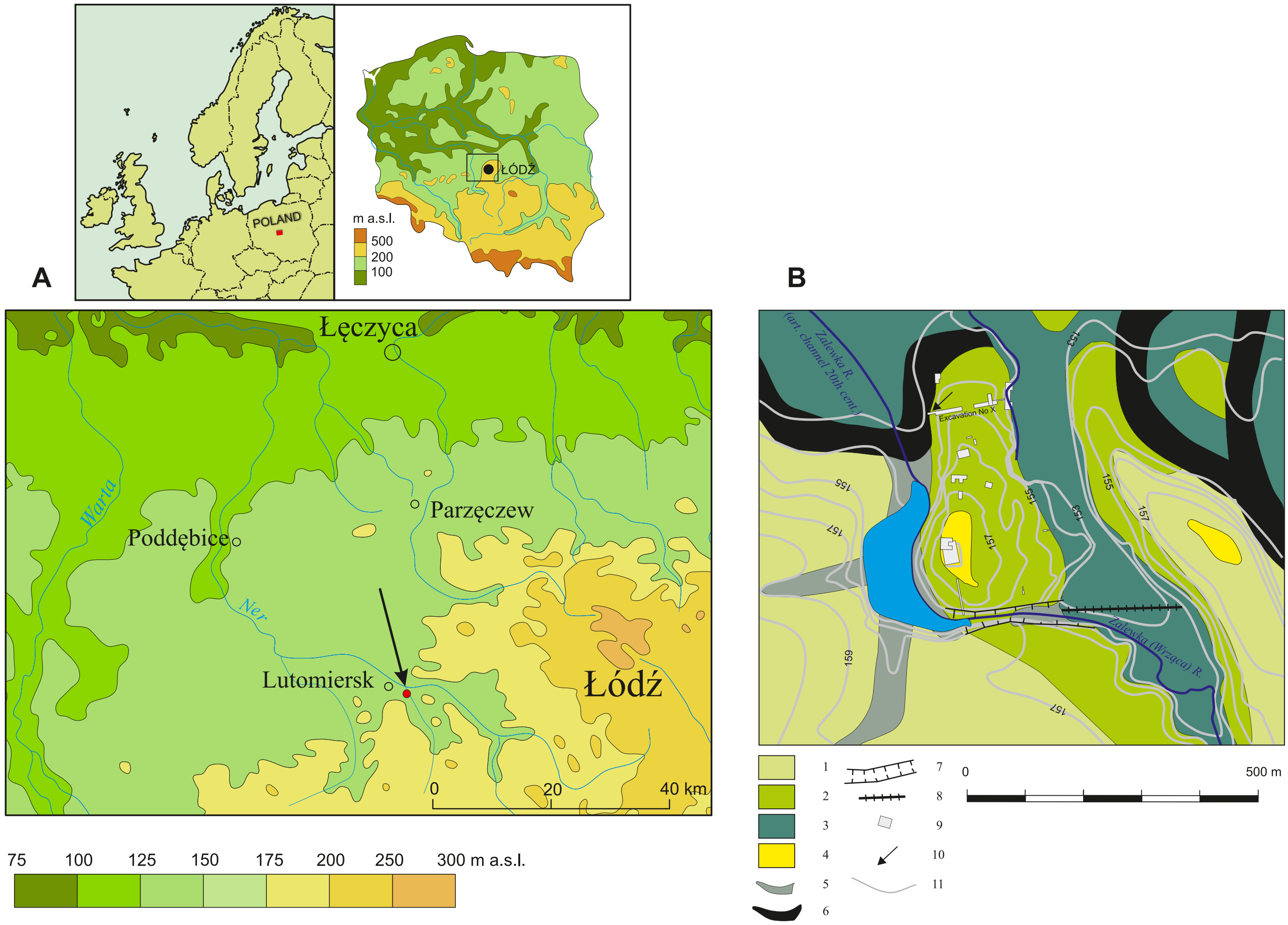

Fig. 1. A). Location of Lutomiersk–Koziówki site; B). Geomorphologic map of the area surrounding the Lutomiersk–Koziówki site 1 – highest terrace (Wartanian termination); 2 – high terrace (Weichselian Pleniglacial, Plenivistulian); 3 – valley floor (Late Weichselian and Holocene); 4 – dunes and aeolian sands sheets (Late Weichselian and early Holocene); 5 – denudational dry valleys; 6 – large-scale palaeochannels (Late Weichselian); 7 – anthropogenic cuts (late Holocene, modern period); 8 – bank; 9 – location of archaeological excavations; 10 – contour lines.

early Holocene fills of the large palaeomeander and middle Holocene overbank deposits in this area (Fig. 2, sygn.: 17–23). The age of the flood deposits has been documented by geomorphological research (Kittel, 2012a) and by the pollen analysis.

The excavated feature is U-shaped in cross-section, 10 m wide in the upper part and filled by organic mud in the bottom. The bottom of the ditch is situated about 2 m below the present day surface. The continuation of the ditch has been partly recognised by geomagnetic survey. The area was strongly altered in the most recent period. Greenish grey organic mud occurs in the lowest part of the ditch (Fig. 2, sygn.: 11) and was covered by organic mud, stratified with sands and ripple laminated various-grained sands and silts with organic admixture (Fig. 2, sygn.: 10A-10). Deposits with organic admixtures reach 70 cm thickness and contain fragments of discarded or removed wood construction elements in the upper part, and clusters of plant stem fragments. Fragments of *Linum usitatissinum* perianth, collected from the profile at a depth 165–170 cm (Fig. 3), have been dated to 330 ± 30 conv. BP (Poz-50355) *i.e.* AD 1521–1644 (1δ range). The radiocarbon date of the wood remains in the upper part of the organic deposits (about 150–160 cm b.g.l.) was 170 ± 40 conv. BP (LOD-1581) *i.e.* AD 1665–1952 (1δ range).

The sword of type 17 after Oakeshott (1960) was uncovered in the bottom of the relict rettery, below the organic mud with dead flax fragments. Sword type 17 is dated to the second half of 14th and the first half of 15th cent. AD, but the sword from Lutomiersk–Koziówki can be more accurately dated to the second half of 15th cent. AD. Swords of the same type are known from Tarnów, Kraków, Raciborz and from the tomb of King of Poland Kazimierz Jagiellończyk from 1506 in Kraków (Rybka, 2012).

Organic mud and sandy organic deposits filling the rettery relicts are covered by various-grained cross-stratificated sands with gravels, planar and low-angle cross-stratified sands and ripple and horizontal laminated sands and silts (Fig. 2, sygn.: 5). The thickness of these sediments is 0.5 m. The most coarse-grained and most poorly sorted sediments occur in the bottom of the unit. The sediments have been deposited in a very dynamic environment, interpreted as the filling of a flood flow channel (Kittel, 2011). Deposition processes took place after the destruction of the rettery equipment and they overlay the rettery relicts.

3.2. Historical sources

Lutomiersk gained city rights in AD 1274 because it was one of the most important medieval settlements in the area and was one of the first settlements in Central Poland (Zajączkowski, 1966). From the 14th until 18th cent. AD Lutomiersk was in the possession of the nobility.

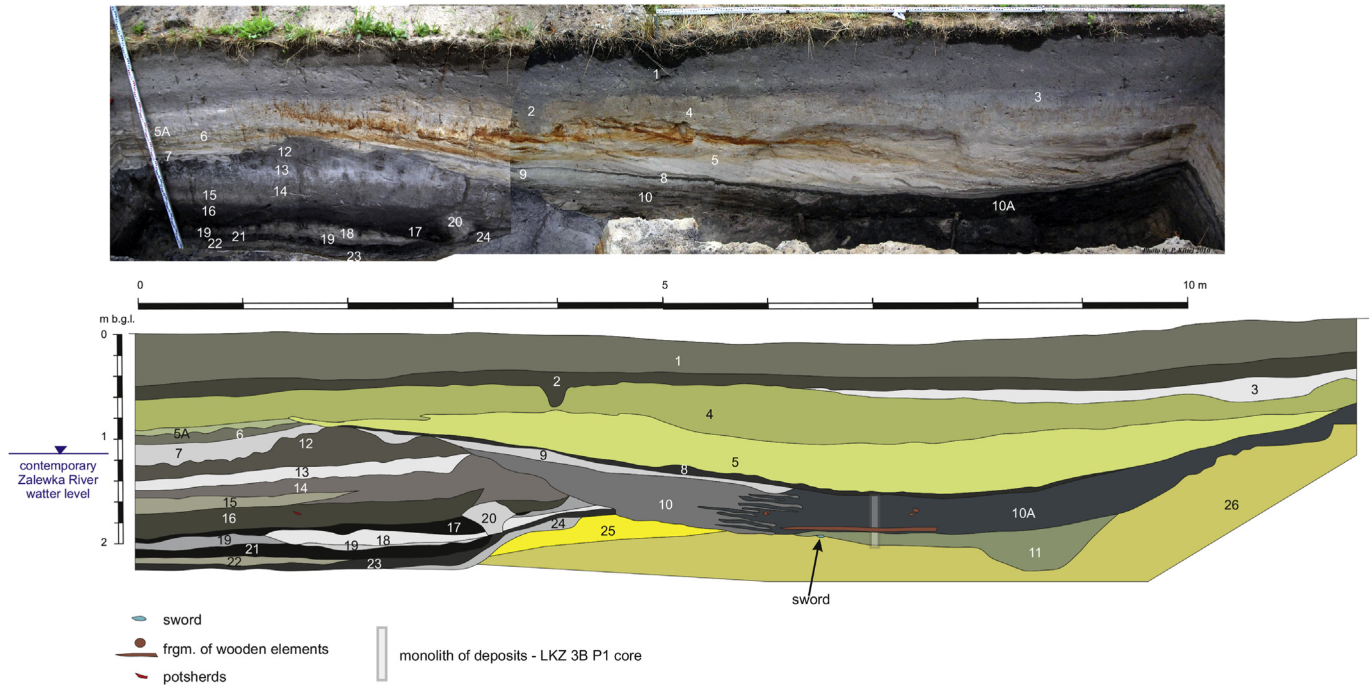

Fig. 2. Lutomiersk–Koziówki site, excavation No. X, wall N. Geological cross-section 1 – various-grained sands (modern berm); 2 – various-grained humic sands (buried soil, modern potsherds); 3 – partly humic various-grained sands (colluvial cover); 4 – overbank non stratified various-grained sands (overbank alluvial deposits, medieval and modern potsherds); 5 – cross- stratified sands with gravels, planar and low-angle cross- stratified sands (fill of overbank flow channel); 5A – ripple and horizontal laminated sands and silts (overbank alluvial deposits); 6 – laminated sands and organic mud (overbank alluvial deposits); 7 – weakly silty various-grained sands (overbank alluvial deposits); 8 – weakly organic mud (overbank alluvial deposits, basin fill); 9 – ripple laminated various-grained sands (basin fill); 10 – ripple laminated various-grained sands and organic mud (basin fill); 10A – organic mud stratified by sands with fragment of wooden elements (basin fill, modern potsherds); 11 – organic mud with bunches of flax (basin fill, modern potsherds); 12 – humic various-grained sands with charcoal admixture (buried soil, Bronze Age and Roman Period potsherds); 13 – weakly humic medium-grained sands with charcoal admixture (deluvial deposits, Bronze Age and Roman Period potsherds); 14–15 – weakly humic medium-grained sands with charcoal admixture (deluvial deposits, Bronze Age potsherds); 16 – humic medium-grained sands with charcoal admixture (deluvial deposits, Bronze Age potsherds); 17 – medium-grained sands and organic mud (buried soil); 18 – coarse-grained sands (deluvial deposits); 19 – various-grained sands with organic admixture (deluvial deposits); 20 – various-grained sands; 21 – organic mud (overbank alluvial deposits, early and middle Holocene); 22 – medium- and fine-grained sands (overbank alluvial deposits, early and middle Holocene); 23 – organic mud laminated with charcoal (overbank alluvial deposits, early and middle Holocene); 24 – medium- and fine-grained sands (colluvial cover); 25 – fluvial coarse-grained sands (Late Vistulian ?); 26 – medium- and fine-grained partly silty alluvial sand (Plenivistulian).

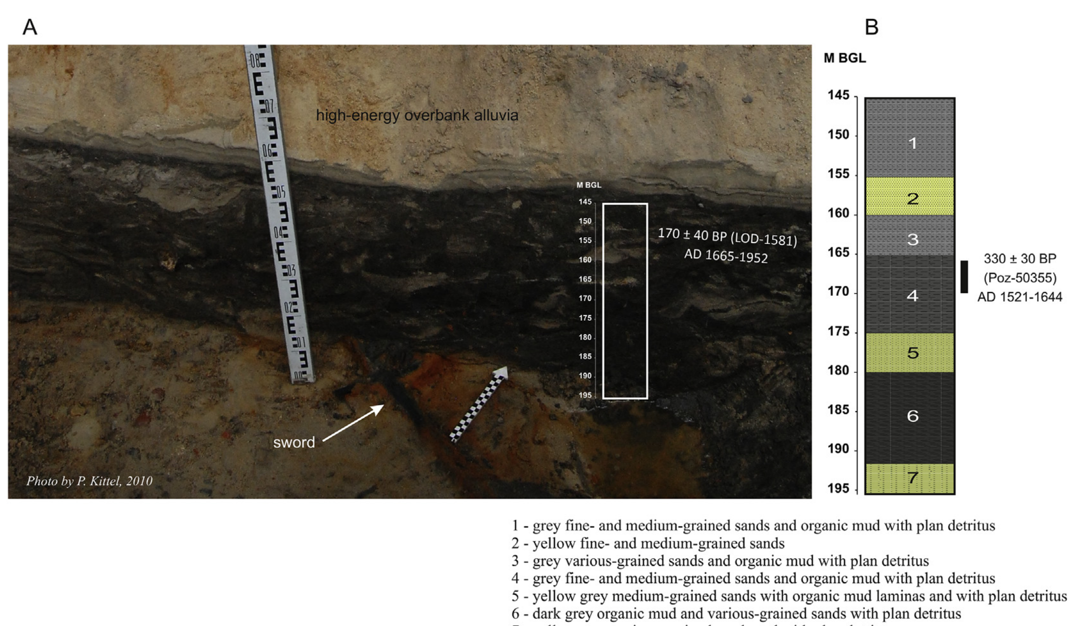

Fig. 3. Cross-section of fills of rettery relicts and location of core LKZ 3B P1 (A). Lithologic profile of the core LKZ 3B P1 (B).

The main written sources for the history of the modern period of Lutomiersk are four council and alderman books from the years AD 1582–1820 (Lut. 1, 2, 3, 4) and the Archive of the Leopold family from Rzepiszew from the years AD 1452–1882 – a collection of documents belonging to subsequent owners of the city (ALzRZ). Additional sources are: the members list of the Draper's Guild for the years AD 1646–1665 (LCS3), the Inventory of Lutomiersk Town from AD 1808 (Lut.5), and Church visits from the second half of the 18th cent. AD (Vis). Cartographic sources come from the second half of the 19th cent. AD.

The character of the city was agricultural. Burghers were also involved in various crafts. At the height of the city (turn of the 16th and 17th cent. AD) about 100 workshops (around 300 properties) were located in Lutomiersk. The most numerous were clothiers – in the 17th cent., almost half of the workshops belonged to members of this profession. Not many references have survived about linen making. The sources from the AD 1582–1671 mention about six linen makers (two-three craftsmen per generation). It is known that some people were involved in making linen as an additional activity. Documents mention two houses which belonged to linen makers. There are records from AD 1640 about one rope-maker. Hemp fibres were important for his business, however sources also mention he was mainly a draper. In cities such as Lutomiersk hemp fibres were important for making strings, bags and ropes, but usually this work generated supplementary income and was not very profitable.

Reconstruction of the layout and ownership of the city shows that the north-eastern part of Lutomiersk, where the linen-wetting pond and a sword have been discovered, belonged to the Lutomirscy family. Analysis of written historical sources shows this constituted a mill named Chabienin and an adjacent pond (perhaps called Chabieński pond).

The first mention of the Chabienin mill and adjacent pond is from AD 1525 (ALzRZ 51: 10–11). The next records are from AD 1592 (Lut.1: 98V) and AD 1598 (Lut.1: 124). In these latter records, the pond was mentioned in addition to the Chabieński mill. The last time Chabienin appears in written sources is AD 1621. The last mention of the Chabieńska river is in AD 1650 (Lut.1: 396v). The mill was located on the Nerzec River, a tributary of the Ner River (ALzRZ 21: 2). Nerzec also appears in sources in which it called the Black Stream and the Chabieńska River; it is now called the Zalewka or Wrząca River.

The part of the city where the Chabienin mill was located was called Koziówki. There were gardens here belonging to the citizens of the town. The name Koziówki appears in documents for the first time in AD 1571 (ALzRZ 45: 9–11). The information from AD 1596 refers to the river flowing here (Lut.1: 111). The record from AD 1697 mentions a road to Mirosławice (east direction) running through Koziówki (Lut.1: 528).

The Chabienin mill was probably already operating in the second half of the 15th cent. AD. Indirect evidence suggests that it may have been the oldest mill in the town, belonging to the mayor, with origins in the 13th cent. AD.

3.3. Flax and hemp cottage processing

Due to the lack of detailed historical information about the process of flax and hemp production, it was necessary to use twentieth-century descriptions. Traditional cottage methods of hemp and flax cultivation, processing and fibre production are well described in monographs of Dowgielewicz (1954), Zdrojewski (1955) and Ejstrud (2011), but they can still be remembered by older farmers from central Poland, as they were widely used in Poland before the mid-20th cent (Józef Płóciennik pers. comm.). Flax was grown on good soil, crops were harvested in August and September, then the straw was dried. Seeds were separated by thrashing. After rippling, the straw was retted. Retting was a process in which the flax or hemp was subjected to fermentation. The process dissolves lignin and pectin binding the fibres with other plant tissues. There are two methods of retting: water retting and dew retting (Zdrojewski, 1955; Ejstrud, 2011; J. Płóciennik pers. comm.).

Water retting might be undertaken in natural water bodies, but this was avoided and even forbidden. Some of the bacteria that flourish in the process of retting are important pathogens that cause dangerous diseases. Also water pH strongly decreases during flax or hemp straw retting, causing water pollution and fish kills. In the early 20th cent. Polish cottage industry, retteries were rectangular holes (about $4 \times 8 \times 1.5$ m) (Fig. 4). Their walls were covered by fascines to protect the straw from minerals washing into the water and reducing the fibre quality. Retteries were located in a cascade of pools linked by ditches bringing water from small streams. Fermentation in water retting is based mainly on bacterial action and needs relatively high water temperature, from 10 to 15 °C, and start to be effective at 20 °C. The second important factor for retting is pH. Because water acidification stops bacterial development the water had to be refreshed frequently.

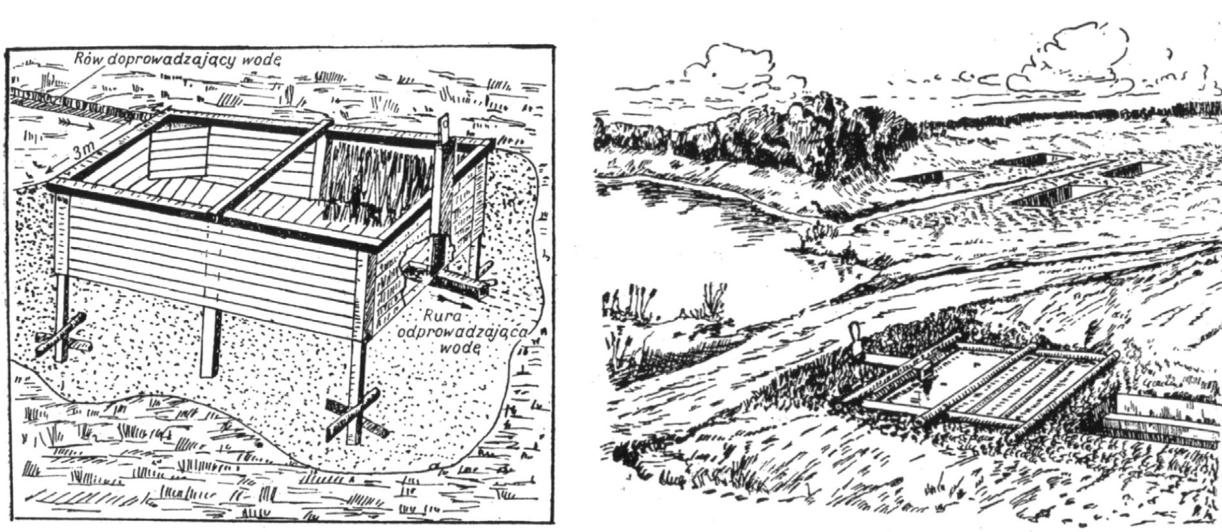

Fig. 4. Rettery draft after Zdrojewski (1955).

If the water temperature remained at about 20 °C, the first part of the retting process took no longer than two to three days. After that time, water was refreshed to remove organic acids, soft tissue particles and the inorganic fraction. The second part of the retting process also took about two to three days, during which most of the pectin was dissolved. The water then had to be refreshed a second time to remove the products of the retting process and most of the bacteria. After this, the process was slower. In central European climatic conditions, water retting took about one to two weeks. Then the flax had to be washed in cold, flowing water and completely dried. Retting could be also stopped earlier and then continued if the straw was not sufficiently decomposed. When retting was stopped for a short period, the straw was dried and the retted again, to produce better quality fibres (Zdrojewski, 1955; Ejstrud, 2011).

Flax cottage technology did not differ much from hemp processing. Hemp is planted mainly as a source of fibre, but also of oil, extracted from the seeds. The species is dioecious, *i.e.* includes male and female individuals. As the quality of fibres depends mostly on the maturity of plants, and also on their sex, in order to obtain fibres of the highest quality and hemp seeds, the male and female plants were commonly pulled out of the ground and retted at a different time (Dowgielewicz, 1954). In the stems of male plants, the finest fibres are found during the pollination period or shortly thereafter. Therefore, male plants were pulled out and retted first, while female plants were pulled out ca. three to four weeks later, providing time for the development and maturation of seeds. They were retted mostly after seed removal. Fibres obtained from female plants were less fine and more fragile, however they do provide mature seeds.

4. Material and methods

A wide range of multi-proxy analyses have been used to develop a detailed understanding of the history of the rettery, the manufacturing processes used and how the rettery became abandoned. During excavation works, specialized analyses have been undertaken including: stratigraphical, structural and textural geochemical analysis of uncovered deposits. The core LKZ 3B P1 of bottom deposits of the rettery relicts was collected as a monolith into a metal box of dimensions of 50 × 10 × 5 cm (Fig. 3). The material was taken so that the structure remained undisturbed. It covers deposits between 145 and 195 cm below ground level. Samples were taken at 5 cm intervals in 1 cm slices (*i.e.* 147–148 … 192–193 cm) for pollen, diatom and Cladocera analyses. Samples for sedimentological, geochemical, plant macrofossils, fossil wood and charcoals, Chironomidae, Coleoptera and other insect analyses were taken as contiguous 5 cm slices (*i.e.* 145–150 … 190–195 cm).

4.1. Geological and geochemical survey

The main geochemical analyses of the sediment taken from core LKZ 3B P1 were: pH, calcium carbonate ($CaCO_3$), organic matter (Loss-on-Ignition, LOI) and biogenic silicon dioxide (SiO_2). The calcium carbonate content was determined by volumetric methods using Scheibler's apparatus. The Scheibler metohd is widely used to estimate $CaCO_3$ contents in sediments and soils (Bengtsson and Enell, 1986; Kaufhold, 2007; Woszczyk and Szczepaniak, 2008). To estimate percentage of Loss-on-Ignition (LOI), samples were fired at 550 °C (Bengtsson and Enell, 1986; Bednarek, 2004). In this ash, the content of biotic and terrigenous silica in the deposits was estimated by removing components soluble in HCl and KOH (Tobolski, 2005). The relative proportions of these compounds can be used to classify organogenic deposits (Tobolski, 2000) and to reconstruct environmental change in the basin and its catchment.

Ash remaining after Loss-on-Ignition analysis was used for particle size analysis using sieve analysis (Rühle, 1973). The weight of samples ranged from 13 to 26 g. The textural features of the minerogenic material were evaluated using Folk and Ward (1957) coefficients. The relationship between mean grain size and the sorting index, the so-called coordinate system after Mycielska-Dowgiałło (1995, 2007), and the C-M pattern after Passega (1964) and Passega and Byramjee (1969) have been marked. The results are presented in a table (Fig. 5).

Radiocarbon (^{14}C) dating was conducted in the Radiocarbon Dating Laboratory in Skała and the Poznan Radiocarbon Laboratory. The OxCal v4.1.7 program was used for the calibration of radiocarbon data (Bronk Ramsey, 2009); atmospheric data are from Reimer et al. (2009).

4.2. Pollen analysis

Samples for pollen analysis were prepared using Erdtman's acetolysis method (Berglund, Ralska-Jasiewiczowa 1986). In each case 1 cm^3 of sediment was used. Silica contamination was eliminated by using 40% HF. *Lycopodium* index tablets were added for the calculation of concentration of microfossils (Stockmarr, 1971). For each sample at least two slides were examined under 400× and 1000× magnification. On average 900 pollen grains of terrestrial plants were counted per sample, as well as all accompanying sporomorphs of reedswamp and water plants as well as cryptogams (Fig. 6).

As the pollen grains of *Cannabis sativa* and *Humulus lupulus* are very similar (Punt and Malotaux, 1984, Whittington and Gordon, 1987; Dörfler, 1990) there are grouped together in the pollen diagram as *Cannabis/Humulus*. The *Cannabis/Humulus* pollen is strongly over-represented and they are treated as a local element incorporated by man directly into the sediment. Their counts are excluded from the basic sum used for calculation of percentage values of each taxon. The basic sum consists of trees, shrubs, and herbs with the exception of local vascular plants and cryptogams. The percentage values of *Cannabis/Humulus* as well as other local taxa (reeds and water plants) and cryptogams were calculated from the same basic sum, increased by the addition of the number of sporomorphs of the particular taxon.

4.3. Plant macrofossils

The analysis included 10 samples taken from the core LKZ 3B P1 (anal. R. Stachowicz-Rybka) and one additional sample (A55D) obtained from a sandy part of the layer 10A (anal. A. Mueller-Bieniek). After the volume of sediment was measured (80–100 cm^3) the samples were macerated according to a standard procedure (adopted by e.g. Stachowicz-Rybka, 2011).

Particular taxa were assigned to habitat groups, following the sequence of their appearance. Two Local Macrofossil Assemblage Zones were distinguished in the diagram (Fig. 7) on the basis of the occurrence of the most numerous or characteristic taxa for the zone. The results obtained from the separate sample (no. A55D) are presented in pie charts (Fig. 8).

4.4. Diatoms

The 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 the 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. Microspheres were added to each sample in order to determine the frequency of the diatoms in each sample (Battarbee

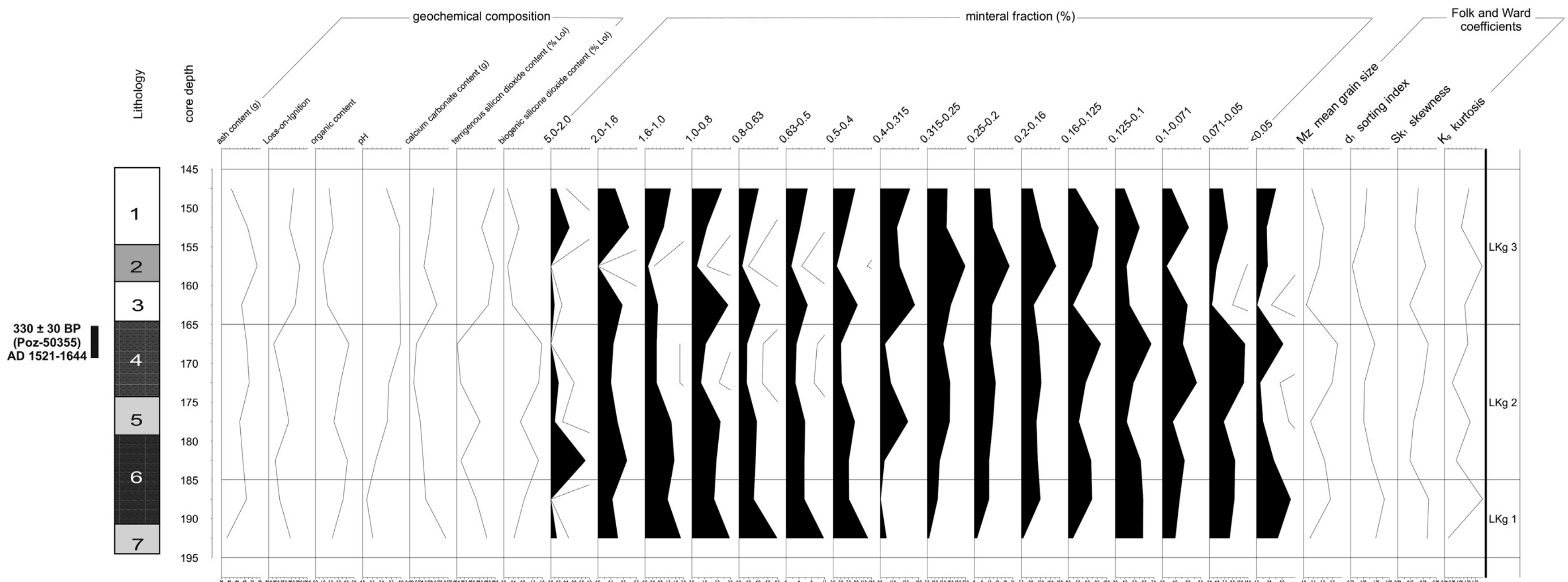

Fig. 5. Stratigraphic diagram of geochemical and lithological composition.

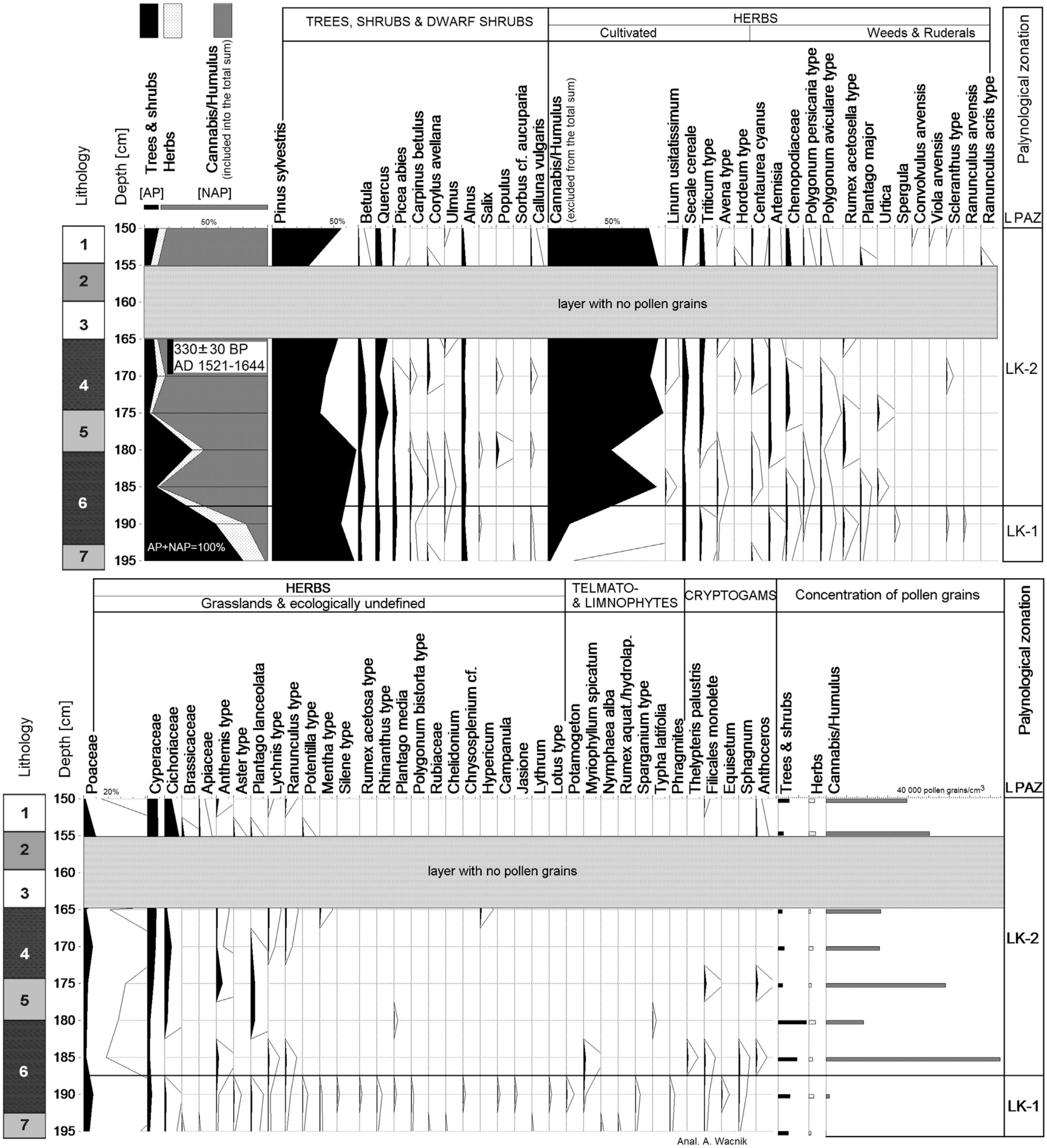

Fig. 6. Percentage pollen diagram and changes in concentration of sporomorphs. *Cannabis/Humulus* pollen counts are generally excluded from the total sum unless otherwise indicated.

and Kneen, 1982). Permanent microscope slides were mounted in Naphrax. The diatom identifications were performed under a Nikon Eclipse E-200 microscope.

Ecological groups of diatoms were determined using OMNIDIA software (Version 4.2) (Lecointe et al., 1993, 1999), and then the resulting groups were distinguished according to Denys (1991/2) and van Dam et al. (1994).The data were obtained from the literature including Lange-Bertalot and Metzeltin (1996), Denys (1991/2), van Dam et al. (1994), Krammer and Lange-Bertalot (2008a,b, 2010, 2011), and Hofmann et al. (2011). In each sample, about 400 diatom frustules were counted in order to estimate the relative abundance of individual taxa.

Reconstruction of pH was performed using Ernie software (version 1.0) (Juggins, 2001) and a combined pH dataset from

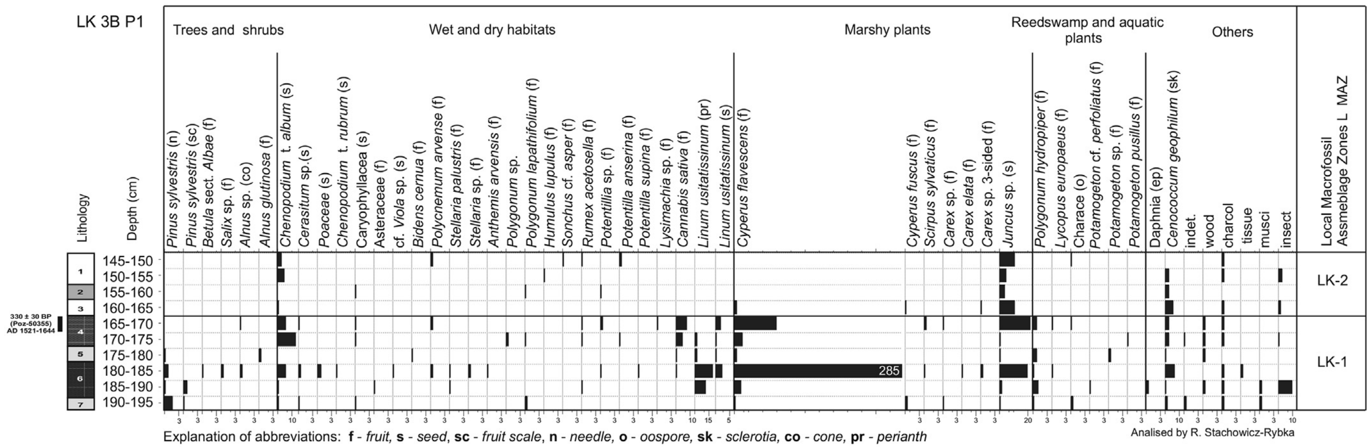

Fig. 7. Diagram of plant macrofossils from the site of LKZ 3B P1.

different regions of Europe: Italian mountain lake dataset, Spanish mountain lake dataset, UCL mountain lake dataset, Norwegian dataset, Finnish dataset, Kola peninsula pH dataset, SWAP dataset and Swedish dataset (e.g. Catalan et al., 1993; Marchetto and Schmidt, 1993; Larsen, 2000; Cameron et al., 1999; Birks et al., 2004). 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 (r^2) of 0.76. Reconstruction of pH was based on diatom taxa which were present at more than 1% abundance in a particular sample because Ernie software automatically excludes the species with the abundance less than 1%.

4.5. *Cladocera*

Cladocera were analysed from 10 samples taken from the core. Samples of 1 cm^3 each were processed according to the standard procedure of Frey (1986): they were treated in hot 10% KOH, and deflocculated using a magnetic stirrer, and afterwards the samples were sieved through a 50 μm mesh. Slides were prepared from 0.1 ml of each sample and examined with a microscope (100× magnification). All remains were counted, including head shields, shells, postabdomens, postabdominal claws, and ephippia. The most abundant body part was chosen for each taxon to represent the number of individuals, and percentages were calculated from the sum of individuals. The taxonomy follows that of Szeroczyńska and Sarmaja-Korjonen (2007). The ecological preferences of

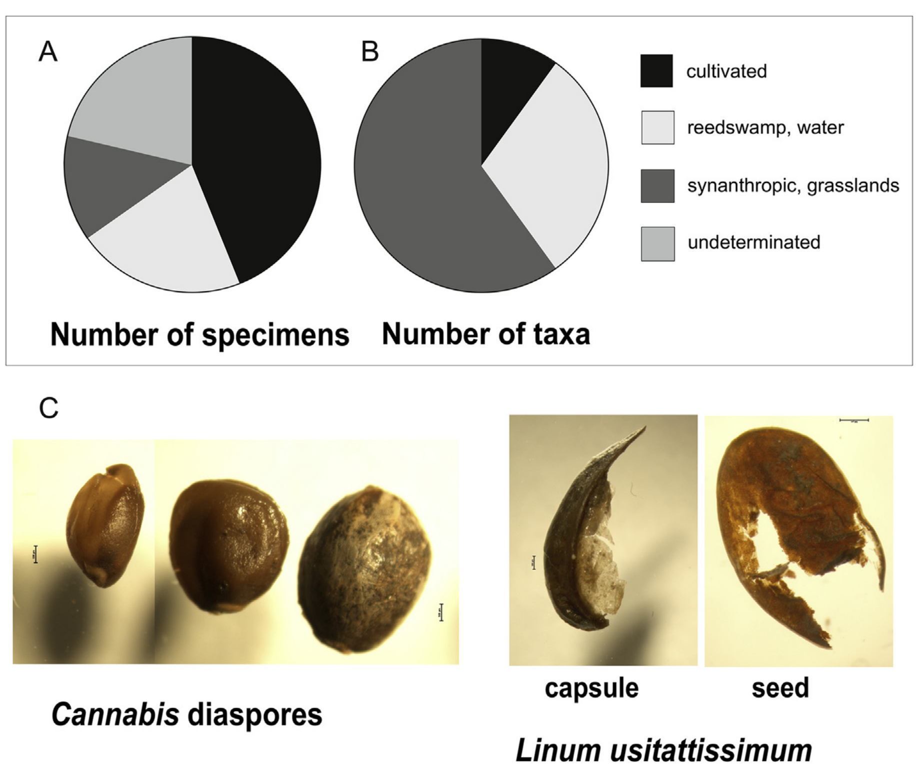

Fig. 8. Plant macroremains (fruits/seeds) found in sample A55D, A – Number of specimens, $N = 164$, B – Number of taxa, $N = 20$, C – hemp (*Cannabis sativa*), selected fruits in different stage of maturity (left), flax (*Linum usitatissimum*), capsule fragment and seed (right), scale bars equal 0.5 mm.

cladoceran taxa were determined on the basis of Whiteside (1970), Szeroczyńska (1998b) and Bjerring et al. (2009).

4.6. Coleoptera

Beetles and other insects were also extracted from the samples taken for chironomid analysis. Because of the small volume of these samples, beetle remains were not numerous. The samples were wet-sieved in a 60 μm mesh, and picked under low-power stereo binocular microscope. Specimens were stored in vials of 60% ethanol, and identified on the basis of comparison with modern museum specimens (Elias, 2010).

4.7. Chironomidae

Chironomids were analysed in 10 samples of volume ranged from 60 cm^3 to 100 cm^3 (mean 84 cm^3). Chironomid preparation methods followed Brooks et al. (2007). The sediments were passed through a 60 μm mesh sieve. Because of the low subfossil concentration kerosene flotation was used following the methods of Rolland and Larocque (2007). Specimens were identified mainly using key of Brooks et al. (2007). Material is deposited in the Department of Invertebrate Zoology and Hydrobiology, University of Lodz. Ecological interpretation follows habitat preferences of the taxa mainly described by Brooks et al. (2007), Vallenduuk and Moller Pillot (2007), Moller Pillot (2009a, 2009b) and the author's personal observations.

The chironomid-based total phosphorus inference model of Brooks et al. (2001) was used to reconstruct log10 TP. The inference model used leave-one-out cross validation and 2-component weighted-averaging partial least squares (WA-PLS) regression and calibration. The model is based on a modern training set of 44 lakes in English Midlands and Wales and includes 72 taxa. The model has an RMSEP (root mean square error of prediction) of 0.34 and an r^2 (coefficient of determination) of 0.60 (Brooks et al., 2001). Fossil data from LKZ 3B P1 has 46 taxa, 34 of which are present in calibration data set. Work by Heiri and Lotter (2001), Larocque (2001), and Quinlan and Smol (2001) has shown that, depending on the diversity of a sample, 50 head capsules can be sufficient to use in palaeoenvironmental inferences. Therefore, reconstruction from the samples in which the number of head capsules was lower than 50 (175 cm, 180 cm) should be treated with caution.

4.8. General numerical methods

Statistically significant zones were determined according to the method described by Bennett (1996), using optimal sum-of-squares partitioning (Birks, 1986; Birks and Gordon, 1985), and testing for statistical significance with reference to the broken-stick model (Mac Arthur, 1957) using the programs ZONE (Lotter and Juggins, 1991) and BSTICK (J.M. Line and H.J.B. Birks unpublished program).

The detailed stratigraphic diagrams of each proxy are presented in separate figures geochemical sediment composition (Fig. 5), pollen (Fig. 6), plant macrofossils (Fig. 7), diatoms (Fig. 9), Cladocera (Fig. 10) and chironomids (Fig. 11). The results are plotted stratigraphically as relative abundance of species (Fig. 7) and percentage diagrams (Figs. 6, 9–11) using POLPAL for Windows software (Walanus and Nalepka, 1999; Nalepka and Walanus, 2003). Fig. 5 was drawn using C2 1.7.3 software (Juggins, 2007) and shows nominal values of geochemical sediment composition as well Folk and Ward coefficients and percentage mineral fraction composition.

5. Results

5.1. Geological and geochemical sediment composition

The samples of ash remaining after Loss-on-Ignition analysis represent the inorganic part of deposits of the LKZ 3B P1 core and consist of sand, silt and clay particles (Fig. 5). Deposits are typified by mean grain-size 1.96–2.61 Phi (φ) (*i.e.* 0.26–0.16 mm), sorting index 0.79–1.54 (*i.e.* moderately and poorly sorted), skewness 0.11–0.29 (*i.e.* fine skewed), kurtosis 0.90–1.43 (*i.e.* meso- and leptokurtic). Frequency curves of grain-size distribution of deposits are bimodal with two peaks: (1) higher – about 2 φ (0.25 mm) and (2) lower – about 4.32 φ (0.05 mm). The inorganic fraction of sediments consists mostly of fine- and medium-grained sand with high admixture of silt. The percentage of mud particles content reaches 10–25%. Only one sample (from 165 to 160 cm) is unimodal and characterised by highest in all profile sorting (0.99) and mean grain-size (1.96 φ, 0.26 mm) indexes.

The relation between the mean grain size and the sorting index represents the second coordinate system after Mycielska-Dowgiałło (1995), characteristic for overbank alluvia or slope wash (deluvial) deposits (Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011). In the C-M diagram after Passega and Byramjee (1969) samples are located mainly within the II class and some samples within I, V and IV class, demonstrating that the analysed sediments have been transported by rolling and suspension (Passega, 1964; Passega and Byramjee, 1969; Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011).

The deposits were found not to contain any calcium carbonate and the pH of the sediments ranged from 4.9 to 6.0. Percentage of Loss-on-Ignition was estimated to 1.6–4.4% and of biogenic silicon dioxide 0.14–1.58%. The geochemical stratification of the profile reflects a three-stage evolution of the Lutomiersk–Koziówki basin. It is believed that the first geochemical zone (depth 195–185 cm core depth) represents a basin with low biological productivity and considerable input of mineral matter from the catchment. In contrast to this, an organic-rich layer (2nd geochemical zone, 185–165 cm) was deposited in a highly productive basin with long-term oxygen deficiency in bottom part of water column. Short-term turbidity in the water basin is also confirmed by a decrease in the number of Cladocera individuals. The third geochemical zone (165–145 cm) represents basin conditions with low water level and considerable input of mineral matter from catchment.

Based on sedimentological and geochemical analysis, we interpret the core deposits with organic and sandy laminas as sediments that accumulated in a small shallow basin with periodic slope wash and overbank deposition. The lower part of the core (*i.e.* below 165 cm) is characterized by the higher content of organic matter (up to 4.36%), biogenic silicon dioxide (up to 1.58%) and generally finer mean grain-size and higher admixture of mud particles. The frequency of deposition of slope wash sediments and overbank alluvia increases in the upper part of the core.

Summarizing, sandy organic mud is recorded between 192 and 180 cm (Fig. 3, sygn. 6). The deposit consists of a high admixture of organic matter and silicon dioxide (Fig. 5). It accumulated in a shallow basin depositional environment. Evidence of intensive flows was observed above a depth of 180 cm (based on decreased of mean grain-size and sorting index). Laminas in sandy deposits were recorded within the lower part at depths from ca. 180–175 cm (Fig. 3, sygn. 5); these were also characterized by a decrease in LOI (Fig. 5). Organic mud with the highest LOI was present at 165–175 cm (Fig. 3, sygn. 4) and was probably deposited during low-energy flows. This is recorded as discrete laminations. The coarsest deposits are present at the depth ca. 165–155 cm (Fig. 3, sygn. 3–2). They are characterised by the highest level of sorting

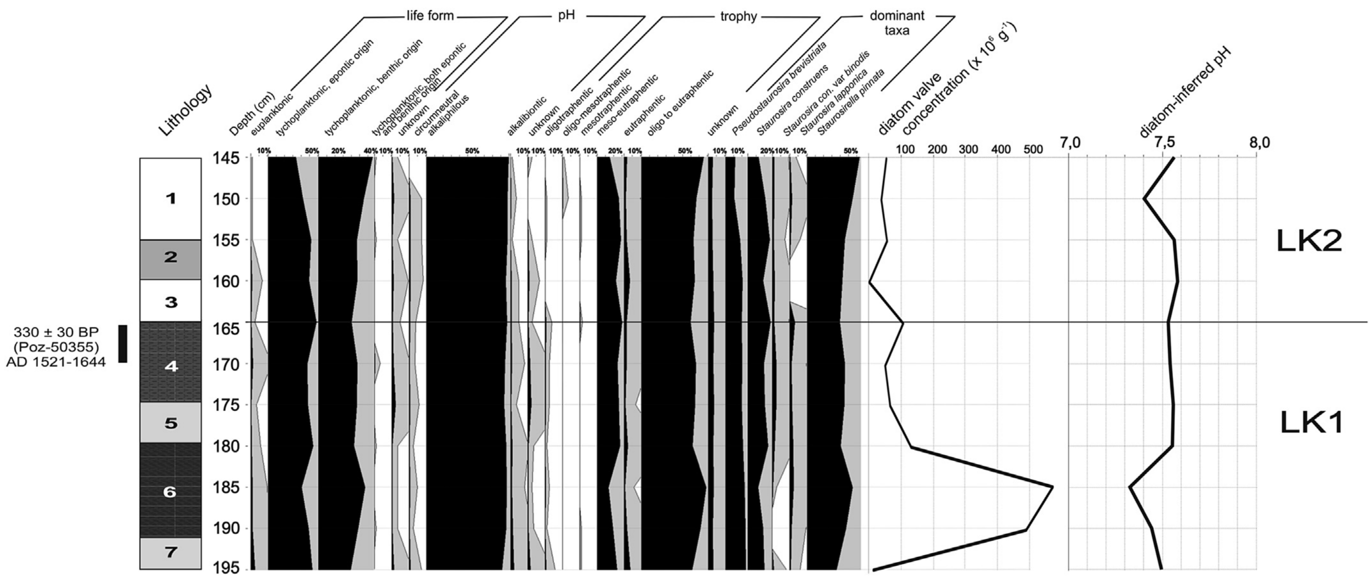

Fig. 9. Percentage stratigraphic diagram of diatom microfossils with pH reconstruction.

and the lowest organic matter admixture resulting from an increase in energy of depositional environment.

5.2. Pollen analysis

The differences in the taxonomic composition of pollen spectra indicate two zones in the palynological sequence from the core LKZ 3B P1 (Fig. 6).

The lower zone L PAZ LK-1; *Pinus* (195–190 cm) is characterized by high representation of arboreal pollen, especially *Pinus sylvestris* (up to 65.4%), which suggests the local presence of surfaces overgrown by patches of pine woods with small admixture of *Picea abies* (2.7%), single *Quercus* (2.1%) and *Betula*. Alder (Alnus) and willow (Salix) pollen is derived from trees and shrubs growing in the wet habitats. The occurrence of pollen grains of cultivated plants such as Secale cereale, Triticum type, Avena type, and Cannabis/Humulus (up to 17.7%) confirm they grew in the vicinity. The pollen record reveals that fields used for crop and hemp/hop cultivation also included weeds of Chenopodiaceae, Rumex acetosella type, Centaurea cyanus, Polygonum aviculare type, P. persicaria type, and Spergula. Pollen grains of reedswamp and water plants, Myriophyllum spicatum, Potamogeton, Sparganium type, and Phragmites as well as Sphagnum spores are present in the bottom samples and confirm that sedimentation took place in a partly overgrown water basin. The concentration of sporomorphs in the sediment is low (<10 000 pollen grains in 1 cm^3 of sediment).

The composition of pollen spectra in the upper zone L PAZ LK-2; *Cannabis/Humulus* (185–150 cm) is strongly modified by direct human activity resulting from incorporation of hemp to the water basin for retting. This is documented not only by the sharp increase

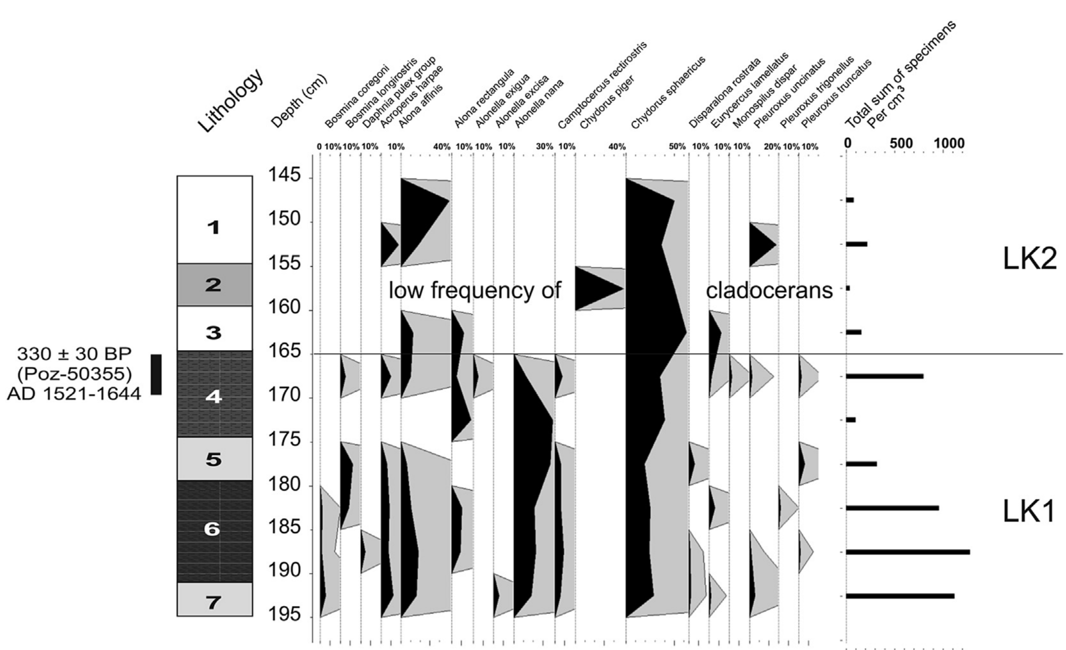

Fig. 10. Percentage stratigraphic diagram of Cladocera sub-fossils.

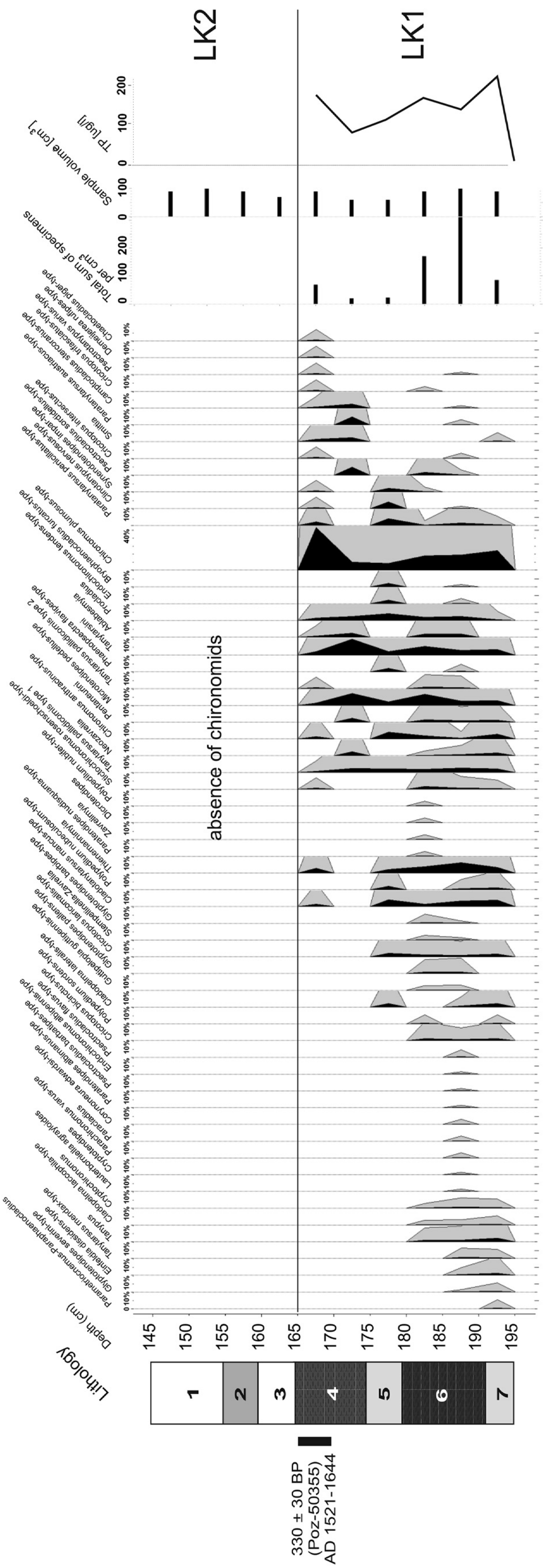

Fig. 11. Percentage stratigraphic diagram of Chironomidae subfossils with TP reconstruction.

of percentage values of Cannabis/Humulus pollen (up to 93.6%), overrepresented in the sediment, but also by the particularly high concentration of its pollen (up to 69 000 in 1 cm^3 of sediment).

The tree pollen record shows a reduction of Pinus sylvestris (average pollen value 50%), a slight increase of Betula (6%) as well as Quercus (10%) is registered. Because pine pollen can be transported over long distances, especially in open environments, the percentage values of its pollen can be overrepresented. Presence of cereals (for example Triticum type (2.5%) and Secale cereale (2.4%)), flax, and hemp/hop pollen confirm they were locally cultivated and that hemp was processed in the water basin. Ruderals and weeds such as Artemisia, Chenopodiaceae, Rumex acetosella type, Centaurea cyanus, Polygonum aviculare type, Plantago major, Convolvulus arvensis, and Viola arvensis are frequent. The pollen of meadow taxa, such as Poaceae, Cyperaceae, Plantago lanceolata, Anthemis type, and Cichorioideae (ca. 2–8%) is numerous. The large amount of herbaceous plants pollen indicates an open landscape.

5.3. Plant macrofossils

Two assemblage zones were distinguished in the examined section of sediments (profile LKZ 3B P1) (Fig 7). The first zone, L MAZ LK-1 (195–165 cm depth), is typified by the presence of seeds and fruit fragments of *Linum usitatissimum* (flax) and fruits of *C. sativa* (hemp). The remains are dominant in the basal part of section, conformable with the initial phase of development of the basin.

During the functioning of the basin, its shores were overgrown by yellow flatsedge (*Cyperus flavescens*), abundant fruits of which were recorded. Today the species is gradually declining in Poland, most likely due to pollution and drying up of sites. Although the species was frequent until recently, but now occurs in only 10–20 localities. *Cyperus flavescens* grows on sandy, humid, periodically flooded shores that are often also trampled and grazed by cattle. This includes the shores of both flowing and stagnant waters (Popiela, 2001). Among the aquatic plants, fruits of *Potamogeton pusillus* and *P. pectinatus* were identified. Boggy areas and ones closer to the shores were inhabited by *Lycopus europaeus* and *Polygonum hydropiper*. The surroundings of the basin were overgrown by tree birches, common pine, willow and alder as well as taxa typical of open areas (*Chenopodium* t. *album*, *Anthemis arvensis*, *Polycnemum arvense*, *Polygonum lapathifolium* and *Rumex acetosella*).

Zone L MAZ LK-2 (165–145 cm depth) indicates a subsequent stage of development of the basin, when it was shallower, filling with alluvial sediment and gradually overgrown. Remains of flax and hemp disappear with the occurrence of an alluvial sand layer that seems likely to indicate the end of functioning of the depression as a retting pit. This resulted in the disappearance of aquatic vegetation, replaced by boggy communities with *Cyperus fuscus* and frequent *Juncus* sp. The remains of plants typical of drier habitats, e.g. *Chenopodium* t. *album*, were observed, similar to the preceding zone. Remains of *P. lapathifolium*, *R. acetosella*, *Potentilla anserina* were also identified. A single fruit of *Humulus lupulus* confirmed the local presence of hop (Fig. 7).

Among fruits and seeds determined in the separate sample (A55D) mostly diaspores of hemp (*C. sativa*) were found (Fig. 8C): a total of 69 were identified, of which 54 were unripe, with tenuous walls and significant stigmas; several remains were preserved only as upper fruit parts with characteristic stigmas (Fig. 8A). The sample also contained flax (*L. usitatissimum*) remains, represented by one seed and several fragments probably belonging to one capsule (Fig. 8B, C). Additionally diaspores of several reed-swamp and water plants were found (*Lemna* sp., *Cy. flavescens*, *Cy. fuscus*, *Rorippa palustris*, *Potamogeton* sp. and Characeae indet.) as well as terrestrial herbal plants, mostly ruderals and weeds (e.g. *Achillea millefolium*, *Anthemis arvensis*, *Camelina microcarpa*, *Chenopodium album type*, *Fallopia convolvulus*, *Linum catharthicum*, *Polycnemum arvense*, *Polygonum aviculare*, *R. acetosella*, *Setaria verticillata/viridis*). No typical flax weed was identified (Fig. 8, Table 1).

5.4. Diatoms

There were 74 diatom taxa identified. The frequency of diatoms in the samples fluctuated between 1.9×10^6 g^{-1} at a depth of 160 cm–545×10^6 g^{-1} at a depth of 185 cm. Planktonic diatoms dominated, which are of tychoplanktonic, epontic or benthic origin, that is so-called random plankton that entered the fossil record when they came off the substrate, or epiphytic species such as *Fragilaria lapponica*, *Pseudostaurosira brevistriata*, *Staurosira construens*, *Staurosirella pinnata*. These species are common in the littoral zone of fresh water, shallow lakes. Many of these species are epiphytic preferring waters rich in nutrients.

The pH analyses revealed a strong dominance of alkaliphilous taxa – the diatoms living in a slightly alkaline environment (Fig. 9). As far as trophic preference is concerned the species with a wide tolerance dominated, from oligo- to eutraphenic. Furthermore, there were many meso-eutraphentic taxa. The reconstruction of pH (7.3–7.6) showed that environment was slightly alkaline.

5.5. Cladocera

The sediments of the LKZ 3B P1 core contain 17 Cladocera species (Fig. 10), belonging to three families (Bosminidae, Daphnidae and Chydoridae). The frequency of the Cladocera individuals ranged from 80 (at a depths 158–157 cm) to 1340 (at a depths 188–187 cm) per cm^3 (Fig. 10). The most abundant are the littoral species of the Chydoridae family. Among the chydorids, *Chydorus sphaericus* is dominant. The species *Alonella nana* and *Alona affinis* are also quite abundant. The abundance of pelagic individuals locally exceeds 10% (Fig. 10) – they are represented by *Bosmina* (*Eubosmina*) *coregoni* and *Bosmina longirostris* and one of the *Daphnia pulex*-group.

The first zone (LK 1 – 195–165 cm depth) is characterized by a high abundance of Cladocera specimens. The most abundant are taxa associated with macrophyte/sediment microhabitats: *A. nana*, *C. sphaericus*, *A. affinis*, *Alona rectangula*, and also in small number – *Acroperus harpae*, *Alonella excisa*, *Alonella exigua* and *Eurycercus lamellatus*. Species such as *Pleuroxus uncinatus*, *Monospilus dispar*, and *Disparalona rostrata*, which are tolerant to fertile/turbulent water, and species preferring warm waters such as *Camptocercus rectirostris*, and *Pleuroxus truncatus* also appeared. Amongst the pelagic forms, the dominant taxon was *B. longirostris*, a species usually inhabiting eutrophic, shallow zones of lakes (Szeroczyńska, 1998b).

The second zone (LK 2 – 165–145 cm depth) is characterized by a lower concentration and decreased biodiversity of Cladocera than in the first zone (with over 300 specimens and 7 species per cm^3 of deposit). Only littoral forms of Cladocera are present, among others, *C. sphaericus*, *A. rectangula* and *A. affinis*. Most of them prefer shallow, eutrophic waters. In addition to macrophyte-associated taxa (*A. harpae*, *E. lamellatus*), the sediment-associated taxa such as *P. uncinatus* and *Chydorus piger* were also quite abundant.

5.6. Coleoptera and insect remains

Remains are present only between 195 and 165 cm of the core (Table 2). In zone LK 1 in depths 195–185 cm both aquatic and terrestrial taxa appear, but the fauna was dominated by aquatic taxa. *Hydrobius fuscipes* is a scavenger water beetle that lives in detritus-rich ponds and bogs. Another scavenger water beetle, *Laccobius minutus* lives in cold, vegetation-rich, acid waters. Larvae of the alderfly *Sialus* live in both running and standing fresh water, and the larvae in the caddisfly family Limnephilidae mostly live in clear lakes and ponds. *Oxytelus sculptus* is a rove beetle found in herbivore dung and piles of rotting plant matter. The red ant genus *Formica* lives in a wide variety of upland habitats. In layers 185–180 cm one water beetle and three upland beetle taxa are recorded, including *L. minutus*, *Anotylus tetracarinatus*, a rove beetle found in herbivore dung and piles of rotting plant matter, and a species of the rove beetle genus *Atheta* that live in damp leaf litter. An unidentified species of the dung beetle *Aphodius* was also found. Thus there is a strong indication of dung on the upland landscape, with adjacent waters that were vegetation-rich. At layers 180–170 cm subfossils of two dung indicators were found. *Oxytelus sculptus* is a rove beetle found in herbivore dung and piles of rotting plant matter, and *Aphodius contaminatus*, a dung beetle associated with cattle, horse, and human feces. In the upper layers of LK 1 (170–165 cm) a mixture of terrestrial and aquatic taxa are recorded. Species of the predaceous diving beetle *Hydroporus* are mostly found in lakes and ponds, though some species live in running water. *Helophorus aequalis* is a water scavenger beetle that lives in detritus-rich standing waters. Larvae of the alderfly, *Sialis* live in both running and standing fresh water. The upland fauna includes *Dyschirius globosus*, a ground beetle that lives on damp open ground of all kinds, the rove beetle *O. sculptus*, and the rove beetle *Dianous coerulescens* that lives in wet mosses by streams. Unidentified species of the dung beetle *Aphodius* were also found. Taken together, the assemblage indicates the presence of both running and standing water. The standing water was rich in vegetation.

Table 1
Taxonomic composition of the sample A55D.

Plant taxa	*
Cultivated	
Cannabis sativa	69
Linum usitatissimum seed	1
Linum usitatissimum capsule (25 fragments)	1
Reedswamp, water	
Cyperus fuscus	1
Cyperus flavescens	17
Lemna sp.	14
Potamogeton sp.	1
Rorippa palustris	1
Charceae indet.	1
Synanthropic, grasslands	
Achillea millefolium	1
Anthemis arvensis	1
Arenaria serpyllifolia (cf.)	3
Camelina microcarpa	4
Chenopodium album type	1
Fallopia convolvulus	1
Linum catharthicum	1
Polycnemum arvense	1
Polygonum aviculare	1
Potentilla cf. *anserina*	1
Rumex acetosella	1
Setaria verticillata/viridis (glumed fruits)	6
Others	
cf. Asteraceae indet.	20
Cyperaceae indet.	2
Caryophyllaceae indet.	1
Poaceae indet. (large grained)	1
Brassicaceae indet.	2
Rumex sp.	1
Potentilla sp.	1
Chenopodiaceae indet.	2
indet. diaspores	5

*Minimal number of reconstructed specimens.

Table 2
Stratigraphy of Coleoptera and other insect subfossils.

Taxon	Sample								
	150–155	155–160	160–165	165–170	170–175	175–180	180–185	185–192	190–195
Coleoptera									
Dytiscidae									
Hydroporus sp.				1					
Carabidae									
Dyschirius globosus Hbst.				1					
Pterostichus sp.				1					
Hydrophilidae									
Hydrobius fuscipes L.								1	
Laccobius minutus (L.)							1	1	
Cercyon sp.							1		
Helophoridae									
Helophorus aequalis Thoms.				1					
Staphylinidae									
Oxytelus sculptus (Grav.)	1			1	1			1	
Anotylus tetracarinatus Block							1		1
Quedius sp.								1	
Atheta sp.							1		
Dianous coerulescens Gyll.				1					
Scarabaeidae									
Aphodius contaminatus (Hbst.)					1				
Aphodius spp.				1			1		
Chrysomelidae									
Chrysolina sp.					1				
Trichoptera									
Limnephilidae									
Genus et sp indet.								1	
Megaloptera									
Sialidae									
Sialis sp.				1				1	
Homoptera									
Cicadellidae									
Genus et sp indet.				1				1	
Hymenoptera									
Formicidae									
Formica sp.					1			5	
Leptothorax sp.						2			
Hymenoptera Parasitica									
Genus et sp indet.				1		1			2
Arachnida									
Oribatei									
Genus et sp indet.				3	2	4	7	2	

Mosses were growing along the banks of running water. Herbivore dung was present on upland surfaces.

5.7. Chironomidae

Remains were present only between 195 and 165 cm of the core. These have been divided to two zones (Fig. 11).

In zone LK 2 (165–145 cm depth) no midge remains were found, while in the bottom of zone LK 1 (195–165 cm depth) midge concentration is relatively high. A total of 55 morphotypes were recorded from zone LK 1. The concentration of chironomids in the sediments decreased rapidly from 180 cm. These changes in midge density may reflect a water level decrease above 180 cm in the core, and terrestrialisation in LK 2. Surprisingly *Psectrocladius sordidellus*-type is the only acidophilic type found, and it appears only in low numbers. Most of the recorded taxa, including the dominants, tolerate high trophic levels in the water and relatively high pH (i.e. *Tanypus*, *Dicrotendipes*, *Procladius, Chironomus plumosus*-type, *Psectrotanypus varius*-type). CI-TP (μg/l) reconstruction suggests hypertrophic conditions throughout zone LK 1 (76-223 TP μg/l). Other taxa, such as *Microtendipes* or *Tanytarsus*, prefer less eutrophic water. These are taxa often found on macrophytes, including rotting plant leaves, such as *Glyptotendipes*, *Lauterborniella agrayloides*, *Endochironomus*, *Polypedilum*. The presence of these taxa may be related to the hemp and flax retting straw which was processed in large amounts in the rettery or to macrophyte vegetation. Phytophilic chironomids are not numerous in the sediments.

Taxa usually found in flowing waters, such as *Thienemannimyia*-type, *Cricotopus bicinctus*-type, *Cricotopus trifasciatus*-type and *Psectrotanypus varius* (pers. obs.), are frequent throughout zone LK 1. This may indicate at least temporary water flow in the rettery which agrees with the general technology and functioning of the rettery as described above. *Camptocladius stercorarius* larvae develop in fresh cow dung which suggests the presence of cattle.

Although there is no evidence from this study that retteries functioned as a series of ponds on a stream rather than as a single pond, this system would have been necessary, especially when the local community manufactured linen, strings, rope and similar products. If such a system was located on the Zalewka River above the excavated rettery, their destruction could have caused the final flood that backfilled the site and they would have been destroyed at the same time. Perhaps local rettery pools were functioning simultaneously (cultivated, aquatic or abandonment, telmatic ecosystem) or in parallel in different stages. After the end of cottage linen production, small flowing streams and rivers were free from pollution and eutrophication caused by this primitive technology. On the other hand, many small water bodies disappeared and with them the aquatic ecosytems.

6. Discussion

6.1. Reconstruction of cultivation

In the investigated retting pit, *Cannabis/Humulus* pollen grains (attaining up to 93%) dominate the pollen spectra, although only a low number of fruits were found (eight specimens in total from LKZ 3B P1). This may indicate separate cultivation of male and female plants, and suggests that male plants were used more frequently in fibre production (Fleming and Clarke, 1998). Additional data obtained from the sample A55D showed clear domination of immature fruits of hemp, also confirming the processing of female plants.

Plant macrofossils analysis of the profile LKZ 3B P1 showed a similar number of seeds and fragments of fruits of *L. usitatissimum* and fruits of *C. sativa*. Results of palynological analysis are contradictory and suggest the strong dominance of hemp/hop pollen grains over flax, which is only represented by single pollen grains. Flax is harvested much later than hemp, after the flowering period, most frequently ca. 7–10 days after flower drop, *i.e.* ca. 2–3 weeks after flowering. Moreover, as flax is an insect-pollinated plant, the pollen is produced in much lower amounts than in the wind-pollinated hemp and therefore is not abundant in the environment (Fleming and Clarke, 1998; Latałowa, 2007). Flax diaspores, like hemp, are a valuable source of oil, therefore are usually carefully collected from the stems prior to their retting. Similar proportions of *L. usitatissimum* and *C. sativa* macroremains were found in the profile, which likely indicates that the pond was used for hemp and flax retting. However, analysis of sample A55D from another part of the same rettery showed a high representation of hemp fruits (mostly immature) and this, together with the pollen record, convincingly suggests that the site was mostly used for hemp retting (Figs. 6 and 7). Fragments of stems preserved in the samples were not identified.

The unique feature of the pollen record was the high concentration of hemp/hop pollen, up to 93% of terrestrial pollen counts. Such a high representation of this pollen type was registered only from deposits filling small ponds used for hemp retting. Some of the highest values of *Cannabis* pollen in the British Isles (up to 90%) have been recorded in the organic muds of Muddymore Pit. Using only pollen evidence this was interpreted as the site being used for hemp retting (Schofield and Waller, 2005). The extremely high Cannabaceae pollen values (up to 82%) at Quidenham Mere were linked by Peglar (1993) to the possible usage of mires and pits along the streamsides for water-retting.

High values of *Cannabis/Humulus* pollen are also known from other European countries, such as France, (70–80%, Lake Pravel; Nakagawa et al., 2000; 40%, site St. Jean; Etienne et al., 2011), Sweden (45%, Bjäresjö; Gaillard and Berglund, 1988), Italy (25%, Lago di Nemi; Mercuri et al., 2002), and Spain (25% Lake Estanya; Riera et al., 2006) and are interpreted as indicative of hemp processing. Pollen sequences from several karst sink holes of less than 1000 m^2 were also found from Czajków in the Staszów area of Poland contained up to 91% of *Cannabis/Humulus* pollen and were accompanied by *C. sativa* fruits (Szczepanek, 1971).

Hemp fruit remains are often considered indicative of retting, especially in the presence of *Cannabis/Humulus* pollen. High amounts of *Cannabis*-type pollen, along with only a few seeds in retting ponds, are interpreted as evidence that predominantly male plants were used for fibre production rather than female plants (e.g. Mercuri et al., 2002). Edwards and Whittington (1992) suggested that the male plants were preferred because they are taller and produce superior fibres. We can assume that such a practice also carried out at Lutomiersk–Koziówki and caused the over-representation of *Cannabis/Humulus* pollen, being incorporated into the sediment directly from the plants put into the water. Although larger water basins were also used for hemp retting, there is little evidence of this process in the palynological record. The percentage values of pollen are usually not very high in Polish profiles for example from Lake Miłkowskie (up to 15%; Madeja et al., 2010; Wacnik et al., 2012, 2014), Lake Racze (up to 25%; Latałowa, 1992), Nowy Folwark (up to 15%; Dobrowolski et al., 2012), Lake Świętokrzyskie (up to 7%; Makohonienko, 2000), and Lake Kęsowo (up to 6%; Miotk-Szpiganowicz, 1992). These values have been considered by the authors as an indicator of hemp cultivation and in some cases also for retting.

A well documented spread of hemp to central and northern Europe is dated from the Roman Period (Dörfler, 1990; Zohary et al., 2012). In Poland widespread hemp cultivation as documented by pollen and plant macrofossil evidence was noted in the Medieval Period (Lityńska-Zając and Wasylikowa, 2005; Latałowa et al., 2007; Badura, 2011; Mueller-Bieniek, 2012), in the 20th cent. AD its cultivation was almost abandoned, and growing hemp for personal use is currently prohibited by law. Hemp has been utilized for its fibres and oil but also as an edible and medicinal plant (Zemanek et al., 2009; Zemanek, 2012). Some uncarbonised unripe hemp fruits were also found in a late La Tène period well in France (Märkle, 2011). Fruits of hemp are commonly found in medieval and modern archaeological sites and can be interpreted as use for food, but immature fruits found in the studied site support the hypothesis of its use for fibre production.

Flax *L. usitatissimum* is another fibre-providing plant found in the sediment. Flax is strongly under-represented in palynological profiles. Very low pollen production and restricted dispersal by mostly self-pollinating flax plants are the main limiting factors which makes the reconstruction of its role in the local agriculture difficult. The timing of a single flax pollen occurrence in the sediment corresponds with a time when the basin was used for *Cannabis* retting. There is no direct palynological evidence that flax was also retted there, but its local cultivation is confirmed by both seeds and capsules (see Latałowa and Rączkowski, 1999). The possibility of flax retting is likewise not recorded by accompanying plant remains. It was noticed in several studies from Sweden that hemp and flax (as in the Lutomiersk–Koziówki profile) occur at the same levels in pollen diagrams, which according to some researchers (Peglar et al., 1989; Regnéll, 1989; Rasmussen, 2005; Rasmussen and Anderson, 2005; Sköld et al., 2010) suggests that they could have been grown together on farms involved in fibre production.

Apart from serving as a retting pit, the basin in Lutomiersk–Koziówki may have also functioned as a livestock watering place, particularly in spring and early summer, when water was not contaminated with rotting stems. This assumption is supported by the presence of particularly abundant fruits of *Cyperus flavescens*, known to prefer shores trampled by cattle, and the remains of dung beetles, that may have been washed into the water basin from its shore, along with cattle dung.

At the end of the use of the depression, a fruit of *Humulus lupulus* was recorded. It cannot be excluded that some of the pollen grains identified as *Cannabis/Humulus*, came from hop as well (Figs. 6 and 7).

According to our palynological results, patches of pine woods with some birch, spruce, and oak occurred close to the site. Moist habitats were suitable for alder and willow (Fig. 6). The open grounds were transformed into cultivated fields and meadows. The occurrence of fields was confirmed by the presence of cereal pollen (rye, wheat and oat types) and most probably hemp. In the later period (but before AD 1521–1644), the cultivated plants were supplemented by flax (also indicated by macrofossils) and barley. The group of segetal weeds and ruderals was represented by *Centaurea cyanus*, *Artemisia*, Chenopodiaceae, *R. acetosella* (also indicated by macrofossil remains), and *P. aviculare* (also indicated by macrofossils), *P. persicaria*, *Plantago major*, *Convolvulus arvensis*, *Spergula*, and *Viola arvensis*. Also some representatives of Poaceae may have grown on cultivated fields. Grasses, together with *Plantago lanceolata*, *Lychnis*, Cichorioideae, and Cyperaceae, were the major component of grasslands and grew on the edges of the basin itself. At the beginning of the sedimentation process the shallow water basin was overgrown by *Sparganium* type, *Rumex aquaticus*/*hydrolapathum*, *Nymphaea alba*, *Potamogeton* and *Phragmites*. The disappearance of water plants and reed-swamp taxa suggests among other things that the hollow could have been cleared of vegetation to optimize its use for retting.

6.2. Reconstruction of water conditions

The first reconstruction of the influence of hemp retting on aquatic ecosystems, based on the response of Chironomidae, molluscs and Ostracoda, was published by Cheng et al. (2007). They show how post-medieval technology of hemp retting affected the trophic conditions and benthic communities of a small lake in England. Quidenham Mere was oligotrophic prior to human impact. Forty-one midge taxa were recorded from the post-medieval period of the lake. Retting caused strong eutrophication and a reduction in dissolved oxygen. Taxa typical of clear water, such as *Tanytarsus lugens* and species associated with macrophytes, sharply declined when hemp pollen increased in the sediment. They are replaced by *Chironomus*, *Microtendipes* and Tanypodinae, taxa which are also recorded from zone LK 1 in Koziówki. The appearance of tanypods in the rettery may also have been the result of acidification. Examples from moorland pools in The Netherlands shows that even natural, strongly acidified water bodies may be dominated by circumneutral taxa preferring eutrophic waters, especially when they are under human influence (eutrophication). Acidification is more clearly shown through predator domination than through the presence of acidobionts (Van Dam and Buskens, 1993). *Procladius* and *Ablabesmyia* are some of the main dominants in Koziówki zone LK-1 while in Quidenham Mere *Procladius* disappeared due to anoxic conditions. The acidification hypothesis is contradicted by the presence of *Ablabesmyia* and *Procladius*, which are abundant in circumneutral water, and *Tanypus* prefers even slightly alkaline conditions. On the other hand, the fossil beetle assemblages suggest acidic conditions (*Laccobius minutus*) in the pond. The Cladocera composition does not indicate acidification of the pond. The Cladocera associated with macrophyte and sediments prefer less eutrophic habitats and warmer conditions, and coexist with few acidophilic taxa (Bjerring et al., 2009). The analysis of subfossil diatoms shows no signs of acidification of the pool. The diatom assemblage is dominated by alkaliphilous taxa and the pH reconstruction shows the lake water was between pH 7.3 and 7.6.

The rapid disappearance of Chironomidae in zone LK 2 seems surprising, given that there were still cladoceran remains in the sediment. Wood et al. (2001) investigated small mill ponds used for the processing of raw wool, the production of woollen textiles or angling. They found that managed and intensively cultivated ponds are abundantly colonized by Chironomidae, even if they were devoid of vegetation. Decaying plant organic matter is a natural food supply for midge larvae, and its accumulation in the water increases chironomid populations (Riley and DeRoia, 1989). After pond abandonment, the macroinvertebrate fauna was dominated by insects larger than chironomids such as damselflies, caddisflies, mayflies and beetles (Wood et al., 2001). In Quidenham Mere, abandonment of hemp processing allowed for the reestablishment of chironomid assemblages found in unpolluted, clear waters (Cheng et al., 2007). In Lutomiersk–Koziówki the rapid disappearance of chironomids in LK-2 was most likely associated with semi-permanent water conditions, as supported by geological and geochemical evidence. Cladocera and diatoms could survive or quickly recolonize temporary pools that appear in the wet season. The larvae of many chironomid species depend on permanent water, however, midges have developed several strategies to survive periodic habitat drying (Bataille and Baldassarre, 1993). There is a surprising lack of subfossils of semi-aquatic taxa such as *Limnophyes* while Cladocera and diatom remains were still abundant. There are also almost no subfossils of other insects, including terrestrial taxa. This indicates conditions (e.g., periodic desiccation, pH) might have been unfavourable for the preservation of chitinous insect remains.

The presence of a few littoral Cladocera taxa in LK 2 zone, which were sediment-associated forms, may be connected with increase of water level, probably as a result of the periodic influence of the river or stream (increase of the water flows). Nevalainen (2011) noted that forms such as *A. harpae* and *C. sphaericus* (sensu lato) have preference for lotic habitats and are also able to resist downstream river flow. The diatoms we found are characterized by a very high abundance of tychoplankton which is composed of benthic/epiplanktonic species brought into suspension by water movements (Vos and de Wolf, 1993; Pliński, 1999). The assemblage is mainly represented by *P. brevistriata*, *Staurosira construens* and *S. pinnata*, littoral species typical of poorly diversified pioneer microflora occurring in shallow lakes (Lotter, 2001; Balwierz et al., 2008). The predominance of tychoplanktonic diatoms provides further evidence for the increase in environmental dynamics in the lake (Lotter, 2001; Bradshaw et al., 2005). This is partly confirmed by sedimentological records of increased energy of the depositional environment and evidence of intensive flows (fluctuations in both the grain-size particles and LOI contents; see Fig. 5). Increase in coarse precipitates above 160 cm may indicate the impact of floods (or slope wash processes). Nevertheless, most of the deposition of organic mud, stratified with sands and ripple-laminated, various-grained sands and silts (between 180 and 160 cm), took place in a depositional basin with low energy flows. The gradual increase of alluvial processes is confirmed by palaeoecological and geological evidence (Figs. 2, 3 and 5). These processes probably occurred during or after the rettery was destroyed. The ^{14}C data from wood records the probable end of the rettery in the second half of the 17th cent. AD.

High-energy flood flow resulted in the deposition of inorganic sands with gravels (Fig. 2), which covered the organic deposits, and took place not earlier than the mid-17th cent. AD. The lack of ponds at the rettery site on maps dated to 19th cent. AD shows that the flood occurred no later than the very beginning of 19th cent. AD. Because of the small size of the Zalewka River, it seems unlikely to have flooded so intensively to produce such a thick and coarse-grained deposition. It is impossible to connect the deposition of those sediments with activity of the Ner River because of the marginal location of the rettery. The deposition of high-energy overbank alluvia and the formation of a flood flow channel within the rettery relicts was probably the result of the destruction of a pond or ponds higher up the Zalewka River valley. A cascade of rettery ponds could have been established on the Zalewka River. The cutting of an artificial channel at the southern end of the site is probably connected with that period and was used to redirect the Zalewka River to establish the ponds. This theory is difficult to verify because of the presence of angling ponds in the area today and because the area has been greatly modified in recent times.

Although there is no evidence from this study that retteries functioned as a series of ponds on a stream rather than as a single pond, this system would have been necessary, especially when the local community manufactured linen, strings, rope and similar products. If such a system was located on the Nerzec (Zalewka or

Wrząca) River above the excavated rettery, their destruction could have caused the final flood that backfilled the site and they would have been destroyed at the same time. After the end of cottage linen production, small flowing streams and rivers were free from the pollution and eutrophication caused by this primitive technology. On the other hand, many small water bodies disappeared and with them the aquatic ecosystems.

7. Conclusion

Organic deposits containing diaspores and pollen of hemp, flax, and other plants have accumulated in a depositional environment suggestive of a rettery as documented by palaeobotanical evidence. The age of a sword and ^{14}C dates of flax demonstrate that the rettery existed in the 16th cent. AD (Fig. 12A) and was out of use by the first half of 17th cent. AD (Fig. 12B). After the mid-17th cent. AD the abandoned basin was subjected to periodic flooding (Fig. 12C) and finally (before the beginning of 19th cent. AD) was covered by overbank deposits (Fig. 12D).

Hemp and flax cultivation was widespread in Europe from the Early Middle Ages to the first half of the 20th cent. AD. For a long time, natural, vegetable fibres were for a long time the main material used for the manufacture of cloth, rope and other artifacts used commonly in everyday life. For this reason pools used in flax and hemp straw retting were frequent elements of the rural landscape. As a habitat for small aquatic ecosystems they had an important role in supporting local biodiversity. Despite being polluted by straw retting products, they were inhabited by a diverse fauna of benthic (e.g. chironomids) and planktonic (e.g. Cladocera) invertebrates. This was possible because of regular water refreshing from local streams. While repeated straw retting in subsequent seasons caused sediment to become acidified, high water trophy and periodic water flow kept the water pH nearly neutral or even slightly alkaline. Aquatic plant vegetation was limited because of drainage, although the diatom flora was well developed. Although rettery banks were usually protected with boards and fascines, sand inwash took place, especially during episodes of floods. This reduced the quality of fibres. Retteries also served as a watering place for cattle, which continued after the processing of hemp and flax ceased. Management of this small pond was necessary to keep the water open as after abandonment the pools were silted by streams and by flooding. Telmatic conditions were less favourable for aquatic invertebrates and diatoms. Aquatic biota were present only during high moisture episodes but rush and reed-swamp vegetation developed.

The system of rettery ponds was established during a period in which the area was owned by the nobility and during intense economical development. Textile production and linen making in Lutomiersk in the 15th–16th cent. AD are clearly documented by historical sources. The rettery relicts are important evidence of this activity. Palaeoecological research provides a detailed reconstruction of the environmental conditions and development of the rettery basin and flax and hemp fibre production in the modern times. The rettery in Lutomiersk is the first modern period feature of this kind uncovered in Poland to be investigated using the methods of environmental archaeology.

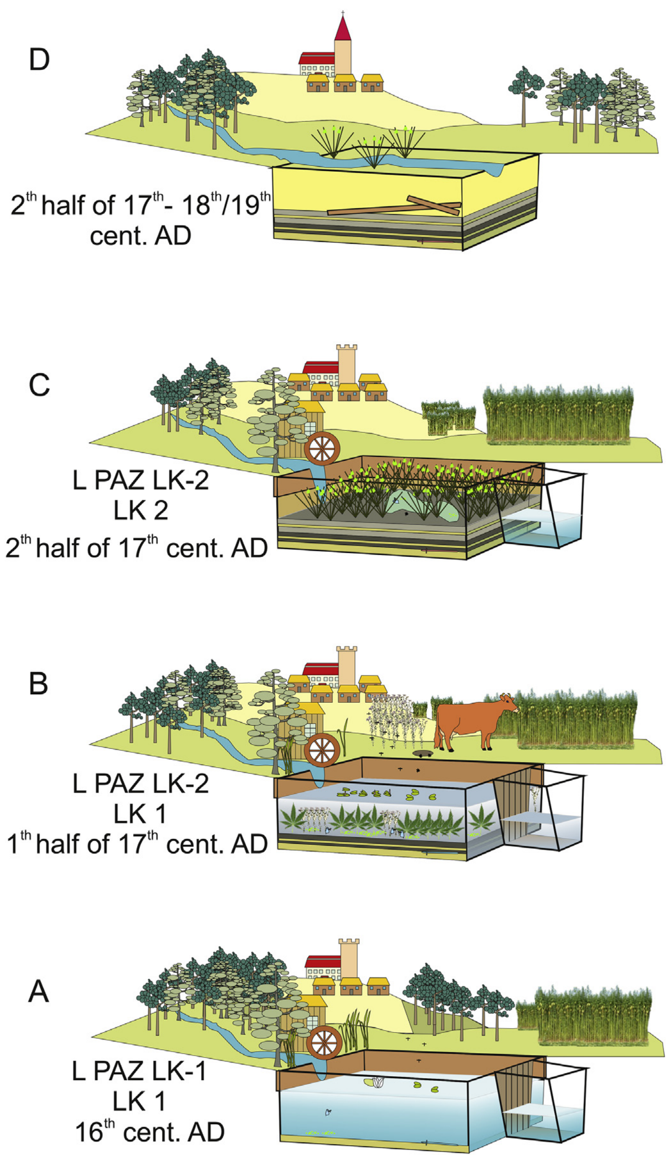

Fig. 12. Summary model of subsequent stages of rettery functioning.

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