EVOLUTION OF SMALL VALLEY MIRE IN CENTRAL POLAND AS A RESULT OF HYDROCLIMATIC OSCILLATIONS

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Abstract: This paper demonstrates the results of analyses of Cladocera, pollen, plant macrofossil, lithological and radiocarbon data recovered from a mire located in the Rawka River valley in central Poland. These studies permit to recognise the development of hydrology phases in Kopanicha mire and give insight into Holocene fluvial dynamics of the system; radiocarbon dating partly allowed dating of the patterns of Holocene valley floor development of the Rawka River. The Kopanicha mire was formed during the Atlantic period. At that time, an oxbow lake formed, becoming a mire during the Subboreal and possibly Subatlantic periods. The high sensitivity of the oxbow lakes, fens, fauna, and flora remains to climate variations – especially to changes in water level connected with the aggradation-erosion cycle of rivers – allows the reconstruction of the palaeoecological changes that occurred in the mire. The frequency and timing of hydroclimatic oscillations at Kopanicha show strong similarities to records from other sites in Poland. Changes in Cladocera frequency and plant assemblages were mostly influenced by the Rawka River which controlled the hydrological regime of the mire. The main factors controlling the presence of Cladocera taxa were the water level and the presence of favourable conditions in the mire (e.g. pH, vegetation). Most of the changes occurred in response to climate changes, but some of them were connected with local factors.

Keywords: valley mire, micro-and macrofossils, river cycles, climate, flood, Holocene.

1. INTRODUCTION

The origin of valley mires may be related to the river environment. These mires are sensitive to the smallest changes in humidity, including drainage changes (Tobolski, 2003). Numerous factors influence the hydrological regime of rivers, which is why the role of oxbow lakes and valley mires is sometimes overemphasized in palaeo-environmental analyses (Mojski, 2005). On the other hand, the significance of palaeomeander infills (valley mires) is great, provided that the local and global factors in hydrological regimes can be distinguished. There is currently relatively little knowledge of Polish mires formed in river valleys (Tobolski, 2003). There are very few investigations of valley mires in central Poland in comparison to other areas of the country (e.g. Żurek,

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1987; Ilnicki, 2002; Tobolski, 2003), despite the fact that most mires in central Poland are located in river valleys. The role of mires and peat-filled oxbow lakes as indicators of changes in fluvial systems due to climatic fluctuations is known in the literature (e.g. Starkel, 1990; Kozarski, 1983; Rotnicki, 1983, 1991; Starkel et al., 1996, 2006). These studies, however, are based mainly on the dating of deposits, and relate these to the major climate fluctuations of the Late Glacial and Holocene. Although the relationship between environmental change, floods, and the Holocene fluvial dynamics of the system have been described (e.g. Rotnicki and Młynarczyk, 1989, Macklin et al., 2006, Schneider et al., 2007; Notebaert and Verstraeten, 2010), these studies have not made use of palaeoecological analysis, in particular of Cladocera analysis.

An identified flood during the Holocene coincides with the phases of lake level rise in mid-Europe, demonstrating a common underlying climatic control (Macklin et al., 2006). Oxbow lakes are affected by changes in the watershed (Schneider et al., 2007), and so many isolated oxbows may serve as useful indicators of both climate change and of human activity. Analysis of plant and animal remains found in such sediments, including plant macrofossils, pollen and Cladocera, are very useful for this.

Using Cladocera – small crustaceans whose remains are preserved in lake sediments, commonly known as water fleas – as bioindicators, we can try to determine and reconstruct the physical and chemical changes in lake environments, as the ecological preferences of these crustaceans are relatively well known. Cladocera species are a good tool for the reconstruction of palaeoenvironmental conditions, including trophic status, fluctuations in water level, and pH in lakes (Korhola and Rautio, 2001). Cladocera analysis enables us to understand the local nature of the changes in biogenic reservoirs, including the transit time of oxbow lakes in mires. The response of Cladocera to changes in thermal and humidity conditions of the climate is significantly quicker than that of other proxies (e.g. pollen). Also correlations between Cladocera frequency and climatic conditions have been previously studied (Lotter et al., 1997; Szeroczyńska, 2006 Kamenik et al., 2007). The initial interpretive possibilities for palaeoecological studies of Cladocera in flood records have been recently demonstrated, and tested mostly with young sediment (from the last two hundred years) associated with human activity (Galbarczyk-Gąsiorowska et al., 2009). To date there have not been many studies which present the use of Cladocera as a trace indicator of past flood events in oxbow lakes. In the past few years, however, some riverine reconstructions of palaeoflow using subfossil insects have been published (Gandouin et al., 2006, 2007; Engels et al., 2008; Howard et al., 2009).

Peat deposits are now more and more frequently considered to be an important source of information about changes in natural environments (Barber, 1993; Moore,

1986, 1991; Lowe and Walker, 1997; Charman, 2002; van der Linden et al., 2008). Of special importance for estimating the hydrological conditions of the site and their dynamics are investigations of the accumulated plant macrofossils in biogenic deposits (Grosse-Brauckman, 1986; Moore, 1986; Tobolski, 1987, 2000; Kloss, 1993, 2005, 2007; Wells and Wheeler, 1999, Birks, 2001, 2003). Determining the geological structure of a mire provides the starting point for the reconstruction of mire history (Tobolski, 2000, 2003). For example, the type of hydrology is reflected in the character of the accumulated biogenic deposits (peat and gyttja). Generally, the species composition of the peat corresponds to the floral composition of peat-forming phytocoenoses in the past (Tołpa et al., 1967; Grosse-Brauckmann, 1986; Kloss, 1993, 2005, 2007; Lowe and Walker, 1997). Reconstruction of the list of species and their combinations based on the analyses of plant macrofossils makes it possible to identify historical phytocoenoses. The botanical composition of peat provides information of the vegetation evolution as well as wetness conditions of the mire since its formation.

The aim of this palaeoecological investigation is to show the connection between the change in the frequency of zooplankton (Cladocera) and plant remains in a small valley mire, and the influences of the river which partly controlled the hydrological regime of this reservoir. This paper provides the first palaeoecological data recovered from the Rawka River valley (central Poland), and also describes the Holocene environmental history, based on selected data (lithological, radiocarbon, pollen, plant macrofossil, Cladocera) from the surrounding Kopanicha mire. The Rawka River valley is a site with a natural or semi-natural river environment character. The results also allowed reconstructions the palaeogeography of the Rawka River valley.

2. STUDY SITES

The Kopanicha mire is located in the central part of the Polish lowlands (**Figs. 1A, B**), near to the town of Skierniewice (geographical coordinates: $\gamma 51°57'10''$N, $\lambda 20°08'30''$E), in the outer part of the valley floor of the valley in the middle section of the Rawka River. The mire is about 1 km to the west of the village of Budy Grabskie ($\gamma 52°00'46''$N, $\lambda 20°12'30''$E – **Fig. 1C**), and covers about 50 ha. The Rawka River is one of the longest tributaries of the Bzura River. Presently, the abandoned channel of the Rawka is dominated by alder swamp (*Ribeso nigri-Alnetum*) with *Alnus glutinosa*, *Betula pubescens* and *Frangula alnus* (Jakubowska-Gabara, 1999). In the marginal zone of the reserve there is a small area of pine wood (*Vaccinio uliginosi-Pinetum*). Today, Kopanicha is a drained mire, with boggy soil to a depth of 20 cm.

Some aspects of the history of the Rawka River valley have been described on the basis of geological (Brzeziński, 1998), geomorphological (Kobojek, 2000,
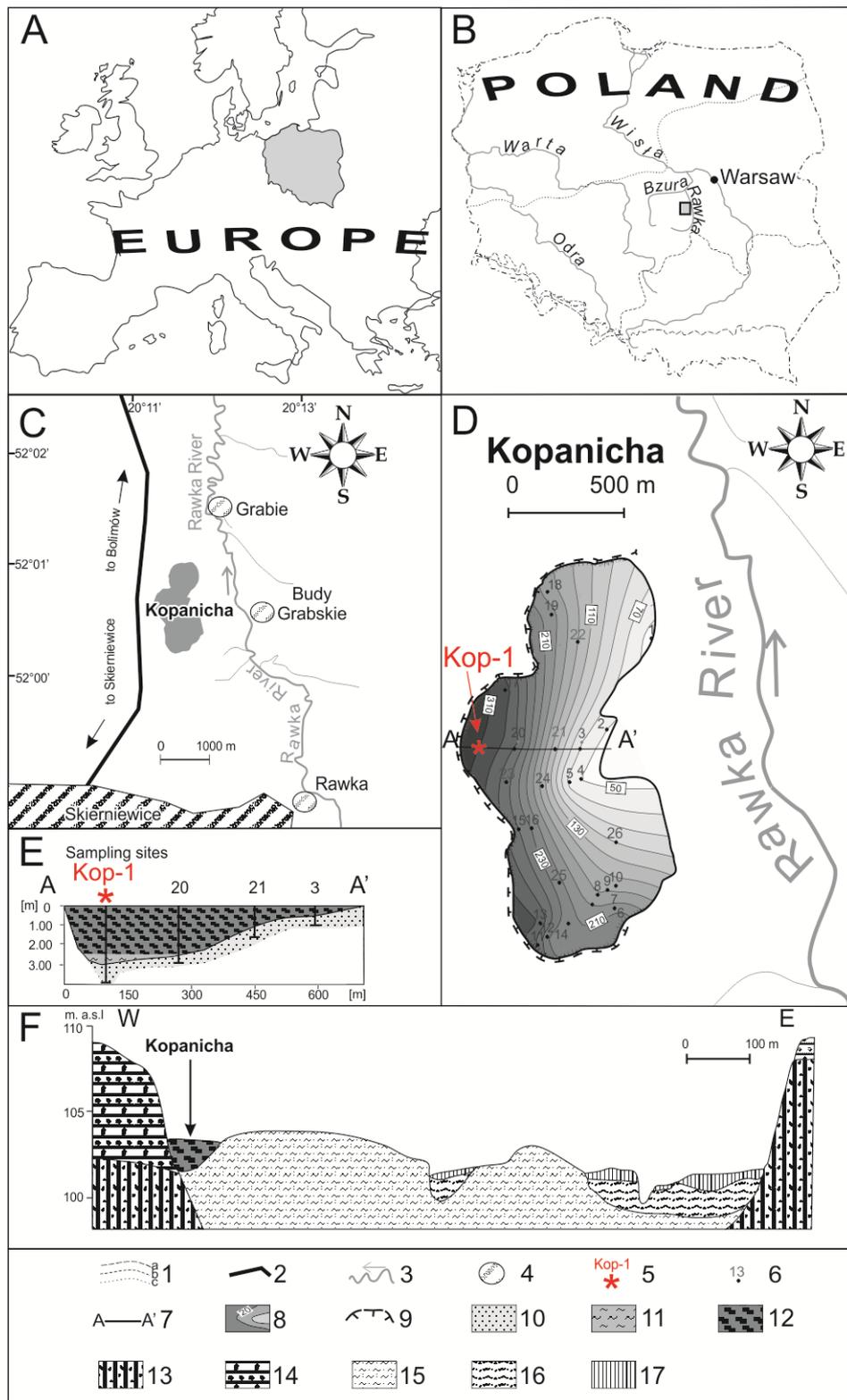
Fig. 1. *Location in Europe (A) and Poland (B, C) of the Kopanicha mire, with map of peat thickness (D), and geological sections: of the studied mire (E) and Rawka valley near Budy Grabskie village (F – after Kobojek, 2009, modified). 1: range of Polish Glaciations: a-Elsterian, b-Saalian, c-Weichselian; 2: main road; 3: rivers, streams, and their outflow directions; 4: towns, villages; 5: location of the studied core (Kop-1); 6: location of the assistant cores; 7: geological cross-sections; 8: thickness of biogenic filling the Kopanicha mire basin; 9: escarpment; 10: fluvial sand; 11: mineral-organic silt and sand; 12: peat (Holocene); 13: till (Saalian); 14: fluvioglacial sediments (Vistulian); 15: sand and silt (Vistulian); 16: riverbed sediments (Holocene); 17: overbank sediments (Holocene).*

2009), and peat characteristics (Grudziński, 1967; Domińczak and Okupny, 2010; Krzysztoń, 2010), but so far there have been no examinations of Cladocera, pollen, plant macrofossils, or radiocarbon data.

The mire in question is located at the edge of the river valley, near the escarpment of the Rawka River (which is over 10 m high), on a supra-flood terrace built from fluvial sand and silts of the Rawka River (**Fig. 1F**). The escarpment was built up from fluvioglacial sands and gravels beginning from the end of the Wartanian (Saalian) glaciations (Brzeziński, 1998). The base of the Rawka River valley is composed of till, whose origin is also associated with the Wartanian (Saalian) glaciations. The valley bottom is mostly composed of Late Vistulian sediments (sands), which were cut in the Holocene by active river channels. The Rawka River of that time has been modelled as a meandering river system (Kobojek, 2000; 2009).

In the section of the valley studied here, the river creates a semicircular depression. The mean peat thickness is about 3 m (**Figs. 1D, E**).

The climate in Poland is transitional, but in the study area is rather continental and drier than in the northern part of country. The mean annual precipitation is 550 mm (Jokiel, 2004). The mean monthly air temperature varies from -3,5°C in January to 18°C in July, with a mean annual temperature of 7.0-8.0°C. Snow cover persists annually for an average of 50 days. The close presence of a large forest area (Bolimowski Primaeval Forest) also probably influences the local wetness conditions.

3. METHODS

Fieldwork

The peat thickness was measured using a gauge auger with a 5 m set of extension rods, and a thickness map was built (**Fig. 1D**). The sediment cores for analysis, Kop-1 and Kop-1a, were collected (using a Russian peat corer) from the location (γ 52° 00′ 45″ N, λ20°11′22″ E) where the thickest peat deposits were found (**Figs. 1D, E**). This is the place in which the analysed section of sand, silt, and peat deposits (from the depth of 380 cm) were located. A parallel hole, Kop-1a, positioned approximately 0.5 m away was extracted with a 5 cm overlap between cores, to ensure that the peat was not compacted and that a complete record was recovered. At the bottom of the deposits filling the depression, fluvial sand and mineral-organic silt were documented at the depth of 380-295 cm. This sand directly underlies peat of the Kopanicha mire. Above, to a depth of about 278 cm, there is mineral-organic silt, covered with peat (278-0 cm) which forms the top of the deposits. All cores were wrapped in foil, placed in gutters, and sealed in plastic.

Pollen analysis

For pollen analysis, 1 cm^3 samples were taken at 5-cm intervals from the 0-380 cm section Kop-1 (at the same depths as for Cladocera). The pollen was prepared and analysed using standard methods, following Berglund and Ralska-Jasiewiczowa (1986): first it was treated with 10% KOH and then acetolysed for 3 min. Minerogenic matter was removed with hydrofluoric acid. One *Lycopodium* tablet was added to the each sample in order to calculate pollen concentration (Stockmarr, 1971). In general, a minimum of 500 pollen grains of trees and shrubs (arboreal pollen, AP) was counted in each sample. Pollen grains of all herbaceous species (except the local aquatic and telmatic plants) were counted as NAP (non-arboreal pollen), and the sum of AP and NAP was taken as 100%. The zonation is confirmed by CONISS (Grimm, 1987). The CONISS dendrogram and the diagram illustrating pollen distribution were plotted stratigraphically by means of Tilia2 and Tilia-Graph (Grimm, 1992).

Cladocera analysis

For Cladocera analysis, 1 cm^3 of fresh sediment sample was taken at 5 cm intervals from the 0-380 cm section of Kop-1, and were processed according to the standard procedure (Frey, 1986): they were treated with hot 10% KOH for 30 minutes, then with a magnetic stirrer to de-flocculate the material, and afterwards the samples were sieved through a 50 μm mesh, diluted in 10 cm^3 of distilled water, and coloured with safranine dye before counting. Slides were prepared from 0.1 ml of each sample and examined under a microscope (100 × magnification). Skeletal remains consisting of headshields, shells, postabdomens, postabdominal claws and ephippia were counted. Five to ten slides were scanned from each sample, depending on the abundance of remains. Percentages were calculated from the sum of individuals. The taxonomy of cladoceran remains in this paper follows that presented by Szeroczyńska and Sarmaja-Korjonen (2007). The ecological preferences of the cladoceran taxa were determined on the basis of Whiteside (1970) and Szeroczyńska (1998). The zonation is confirmed by CONISS (Grimm, 1987). The cluster analysis was based on the constrained incremental sum of squares clustering. Only species with at least 5% abundance at each level were included in the statistical calculations. Results were plotted in a relative abundance diagram using POLPAL software (Walanus and Nalepka, 1999).

Plant macrofossil analysis

For plant macrofossil analysis, Kop-1a was cut at 10-cm intervals from the 0-280 cm section. The collected samples had a volume of about 30-50 cm^3. All macroscopically different layers of the deposit were represented. The material for microscopic studies was boiled in 10% NaOH, and then washed under water in a sieve with a mesh size of 0.2 mm (Tobolski, 2000). A Nikon Eclipse

E 400 microscope was used in the analysis. Isolated plant remains were identified to species, where possible, and the percentage share of each taxon was determined. From each sample, 10 slides were taken to determine the peat composition. Macrofossils were identified with the use of available guides (e.g. Katz *et al*., 1965, 1977; Mauquoy and van Geel, 2007). Also description of the peat decomposition, loss on ignition and pH in water measurement were determined by standard methods used in palaeoecological analyses (Berglund, 1986).

Radiocarbon dating

Radiocarbon dating was performed for bulk samples of organic matter or peat layers from the Kop-1 core. All analysed samples were investigated at the Radiocarbon Laboratory in Skała (Poland), using Liquid Scintillation Counting method. The mass of samples varied between 20 and 30 g. The samples pretreatment was carried out using the standard procedure (Pazdur *et al*., 1986). The results of radiocarbon dating are presented in **Table 1**. Calibration of the radiocarbon dates (expressed as cal yr BP time intervals with probability 95.4%) was carried out using the calibration data set IntCal09 (Reimer *et al*., 2009) and OxCal (version 4.1) calibration program (Bronk Ramsey, 2009).

4. RESULTS

We developed a zonation for each proxy. The detailed diagrams of each proxy are presented in separate figures for radiocarbon data (**Table 1**), pollen (**Fig. 2**), Cladocera (**Fig. 3**) and plant macrofossils (**Fig. 4**). However, we have presented the developmental history in stratigraphy context, which is a useful criterion with regard to the aim of this study.

The results of the radiocarbon dating analysis of sections of Kop-1 (see **Table 1**) point to the Atlantic and Subboreal periods.

History of the Kopanicha mire

The geological structure of Kopanicha mire and its substratum suggest that the basin of the mire was originally associated with a river channel (**Fig. 1D**). The course of the abandoned palaeomeander, whose outer edge was quickly eroded due to the stronger and faster

current, is also clearly visible. A summary diagram and scheme illustrating the development of Kopanicha mire with a brief interpretation is presented in **Fig. 5**.

Atlantic period

Accumulation at the Kopanicha site started in the Atlantic period. This is confirmed by the presence of continuous curves of *Corylus, Quercus, Tilia, Ulmus, Alnus* (**Fig. 2**, Kop1 zone). Additionally, the date at the depth of 336 cm confirms this age (see **Table 1**).

It was in the middle part of the Atlantic period in the Rawka River valley that aggradation of the river valley floor begin (Rotnicki, 1991; Turkowska, 1988; Kobojek, 2000). It was probably at this time (based on pollen and radiocarbon data) that part of the Rawka River palaeomeander was cut off. This is indicated by the position on the floodplain terrace and the slightly elongated, curved shape of the mire basin. Yet the lack of cladoceran remains at depths of 380-350 cm suggests continuous river influence. Fluvial sands, the low frequency of sporomorphs, and the lack of Cladocera (**Fig. 5**) indicate that water conditions in the Rawka River valley showed considerable flow activation in the Kopanicha palaeochannel. The presence of grains of *Potamogeton* – a genus of aquatic plants whose species are found in standing or running water – partly confirms this hypothesis (**Figs. 2, 5**).

Cladocera appear at a depth of 350 cm. The colonization of the reservoir by the Cladocera probably indicates a period during which the reservoir was not under the direct influence of the Rawka River (**Fig. 5**). This period is also marked clearly in the cluster analysis results as a separate branch (**Fig. 3**). The basin was very shallow (95% dominance of littoral species of Cladocera, **Fig. 3**). The first Cladocera zone (KI) is relatively rich, being much more diverse (plant-associated taxa living between submerged macrophytes, and benthic taxa and planktonic species) than typical pioneering assemblages, due to favourable climatic conditions for Cladocera colonization and the oxbow development. The appearance warm water species (Poulsen, 1928) – such as *Graptoleberis testudinaria, Camptocercus rectirostris*, and taxa from the genus *Pleuroxus* – confirms this hypothesis. Such conditions are also partly confirmed by the *Typha latifolia* pollen (a aquatic plant which found in preferably tropical, subtropical and southern temperate humid conditions).

Table 1. *Results of radiocarbon dating of core Kop-1.*

Sample name (Lab.no.)	Depth (cm)	Lithology	Age ¹⁴C (BP)	Calibrated age cal BP (95.40% probability)
MKL-618	63-60	Sphagnum-sedge peat	3190±70	3580-3250 (95.4%)
MKL-619	93-88	moss-sedge peat	3340±50	3690-3460 (95.4%)
MKL-554	120-117	sedge peat with reed and wood	3840±100	4520-3970 (95.2%) 3940-3930 (0.2%)
MKL-556	336-339	mineral-organic silt	7430±110	8420-8020(95.4%)

Fig. 2. *Percentage pollen diagram from the Kopanicha mire (Kop-1 core). LPAZ: local pollen assemblage zones.*
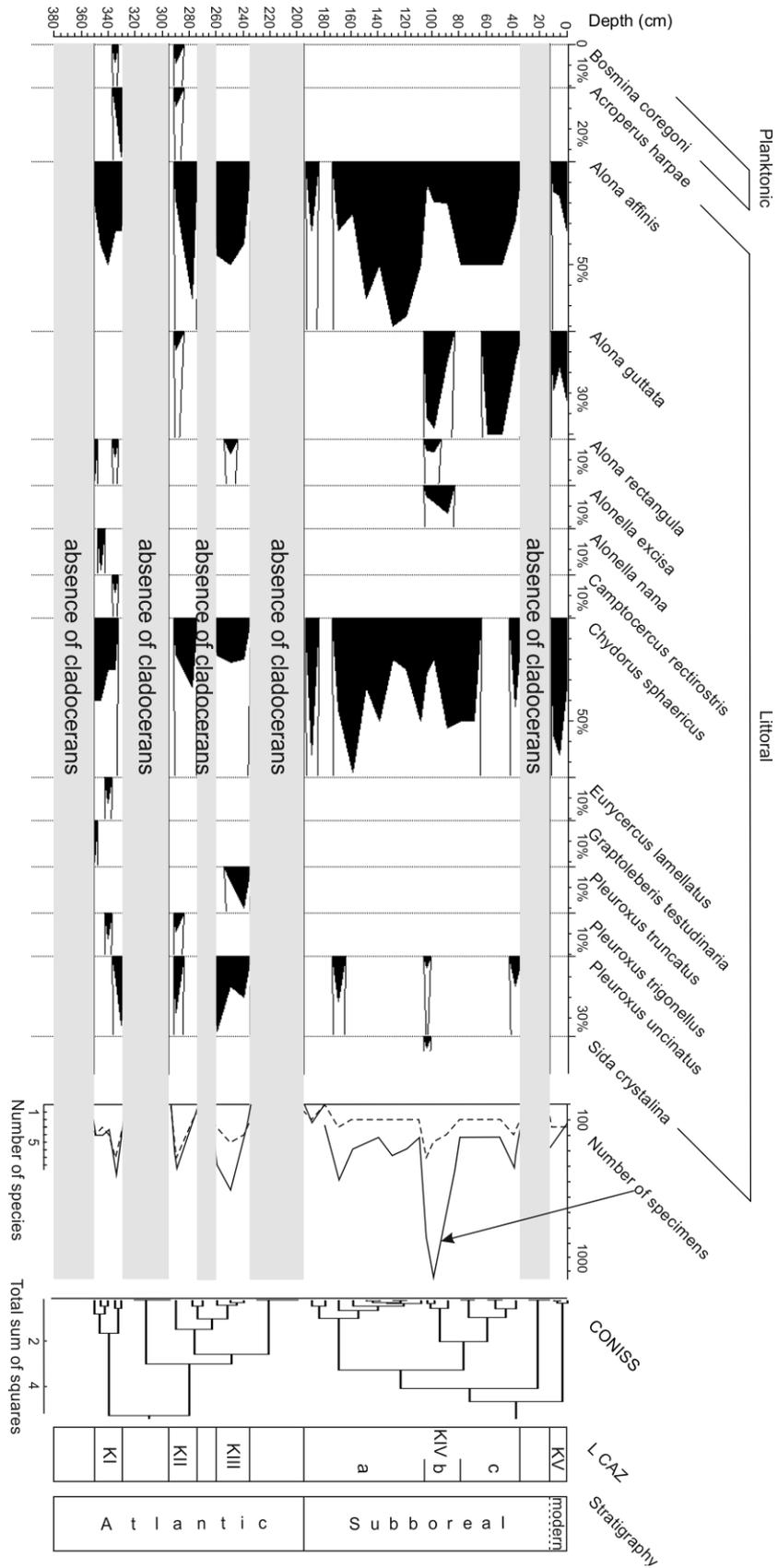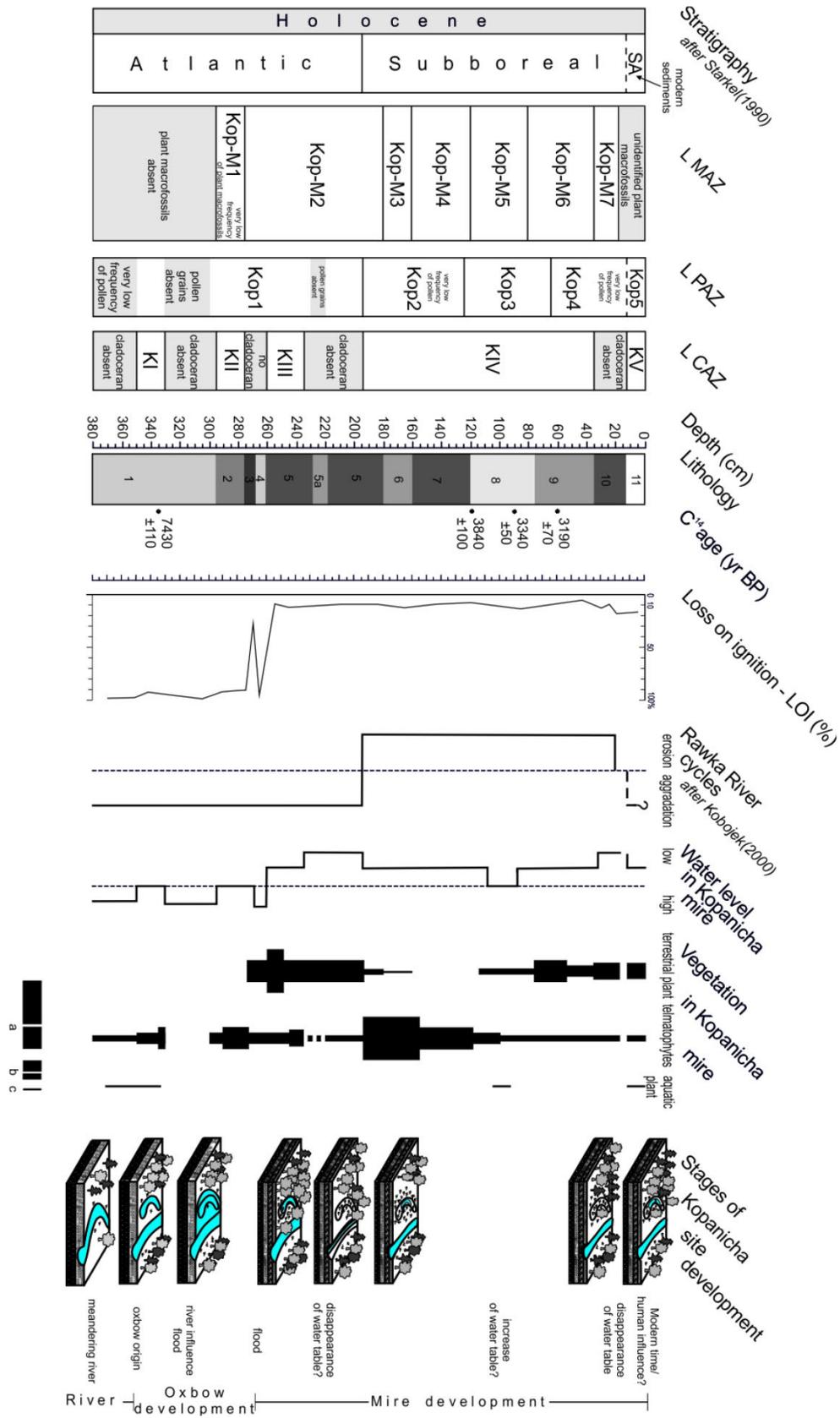
Fig. 3. *Percentage Cladocera diagram, simple numerical analyses of cladoceran data (cluster analysis diagram, CONISS), total number of species, and specimens in 1 cubic cm of sediments from the sediment of Kopanicha mire (Kop-1 core). L CAZ: local Cladocera assemblage zones.*

Fig. 4. *Percentage plant macrofossils diagram from the Kopanicha mire (Kop-1a core). L MAZ: local plant macrofossils assemblage zones.*

Fig. 5. *Summary diagram and scheme illustrating development of Kopanicha mire. a: abundant occurrence; b: regular presence; c: sporadic presence; 1: fluvial sand; 2: silt with sand; 3: sandy peat with fragment of wood; 4: sands with fragment of wood; 5: wood peat (with Alder); 5a – wood peat with reeds, decomposed 6: reed-sedge peat; 7: sedge peat; 8: moss-sedge peat; 9: Sphagnum-sedge peat; 10: transitional peat; 11: mucked peat.*

The influence of the Rawka River probably dates to the end of zone KI (**Fig. 5**). The low frequency of plant-associated Cladocera, the presence of benthic taxa, the increase in soft-bottom dwelling species (e.g. *Pleuroxus uncinatus*), and the appearance of *Bosmina* (*E.*) *coregoni* may all indicate an increase in the water table following flood events. Finally, the absence of Cladocera at depths of 330-295 cm, which may be related to flooding, suggests that the oxbow was then flooded or that the Rawka River was flowing at the time (**Fig. 5**). This hypothesis is supported by the presence of fluvial sand sediments and the lack of pollen in the sediments from that time (**Figs. 2, 3, 5**).

The reappearance of Cladocera at the Kopanicha site may well be associated with the reappearance of the oxbow. Among the littoral forms, soft-bottom dwelling species (*Pleuroxus uncinatus*) predominate, as well as species living between vegetation (e.g. *Alona affinis, Chydorus sphaericus, Acroperus harpae, Pleuroxus trigonellus*), and those which can tolerate a lower pH (e.g. *Alona guttata*). This reservoir was therefore very shallow and functioned only for a short time. This is partly confirmed by the lack of gyttja, typical of lake sediments. Instead, grey silt is found and is consistent with oxbow lake sedimentation, where there were long-lasting floods and changing habitat hydration. Also, the non-calcareous environment probably did not allow the development of rich aquatic invertebrate and plant communities, and/or oxygenated waters, while periodical inflow stimulated of organic matter humification processes.

The decrease in the water level of the reconstructed reservoir and its transformation into a mire is demonstrated by the short-term disappearance of all Cladocera (**Fig. 3**). Pollen analysis shows that the oxbow had already started to disappear in the Atlantic period (**Fig. 2**). The Kopanicha reservoir was overgrown and peat accumulated (**Fig. 5**). Additionally, the presence of peat layers from other parts of the Rawka River valley suggests that the beginning of peat accumulation (that is, the time of transformation of the reservoirs (oxbows) into mires) in the Rawka valley was connected with the end of Atlantic (Kobojek, 2000). At that time, Kopanicha was probably a forest mire with a large number of trees, and the presence of *Alnus glutinosa* remains suggests that the mire was mainly overgrown with alder (**Fig. 4**).

Progressive shallowing promoted cladoceran species that are associated with or largely restricted to plants, and was further characterized by the presence of benthic taxa. These changes are correlated with an increasing number of *Carex* type (**Fig. 2**) and with the presence of *Phragmites australis* remains, although the mire was still overgrown by alder (**Fig. 4**, zone Kop M-2). The continuous presence of forms living in warm waters suggests continuous warm climate conditions. However, the mire may have underwent periodic flooding by the Rawka River. This is documented by the presence of sands with wood fragments, the increased value of LOI (**Fig. 5**), the lack of

Cladocera, and development of *Ribeso-Alnetum* phytocoenose.

The disappearance of Cladocera (**Fig. 3**) at the end of the Atlantic period indicates the rapid development of unfavourable conditions in the reservoir for Cladocera. The mire was able to develop further, but the groundwater level in the studied section of the valley was probably reduced, as indicated by the disappearance of Cladocera and pollen from the sediments. This thesis is confirmed by the presence of strong, well decomposed peat in the core (**Figs. 4, 5**). This may suggest a very low water table of Kopanicha mire caused mainly by decrease in the water table and drainage of the mire. Simultaneous, development of *Ribeso-Alnetum* phytocoenose suggests low water supplies from the edge of the escarpment. The parallel, of both: water table decrease and of Cladocera absence may there here connected with drier phases on the alder mire. The absence of pollen grains was probably caused by differing resistance to corrosion and the consequent unequal preservation of pollen grains from different taxa. In turn, the appearance of the water table and Cladocera may be associated with more humid phases of alder mire development, especially from 220 cm, where a slight increase in water table in the mire can be seen.

Subboreal period

The decrease of the *Ulmus* curve (**Fig. 2**, zone Kop2) suggests that the beginning of the Subboreal period at the Kopanicha site is probably at a depth of 193 cm. This is also partly shown by the radiocarbon data (**Table 1**). During this period, continuous development of Kopanicha mire was taking place, firstly sedge-reed mire, and later moss-sedge mire (**Fig. 4**, zones Kop M3-M5). This is also confirmed by the increasing number of telmatic plants (**Fig. 5**). The reappearance of Cladocera was probably connected with a higher groundwater. The results of plant macrofossil analysis suggest that it is likely that the rather intense inflow of water from higher aquifers had already started. The incoming waters were characterized by a high abundance of nutrients. Initially *Thelypteris-Phragmites*, and later *Caricetum elatae phragmitosum* phytocoenose, developed in the mire. There were no signs of any direct influence of the Rawka River, such as floods (lithological changes). In the Kopanicha reservoir, there were only a few littoral Cladocera species which tolerate specific conditions, such as vegetation density. The water table was low (**Fig. 5**).

It is very interesting to note that the largest number of Cladocera were found at depths of 105-90 cm (**Fig. 3**, subzone KIVb). This period is clearly shown in the cluster analysis as a separate branch (**Fig. 3**), which probably suggests specific conditions. The plant-associated taxa were predominant, but accompanied by other species, such as *Alona guttata, Alonella excisa*, and *Chydorus sphaericus*. The presence of these first two species is strongly correlated to a pH decrease (Korhola, 1990), but not the case here because the presence of *Alona rectangu-*

la suggests even better edaphic conditions. Moreover, the presence of *Pleuroxus uncinatus* continues to point to warm waters. It is possible that this time was associated with an increase in humidity in the mire (a rise in the groundwater level in the Rawka River valley). This is confirmed by the presence of poorly decomposed peat (**Fig. 4**), and also of single pollen grains of *Typha latifolia, Sparganium, Menyanthes trifoliate*, and *Lythrum* (**Fig. 2**, zone Kop3), among which are some aquatic plants (helophytes) of shallow marshes, ponds, and streams. The mire was compared of *Caricetum* with *Carex elata* and *Carex lasiocarpa* phytocoenoses; while *Phragmites australis* also slightly increased (**Fig. 4**, zone Kop M-5). Ash content also increases slightly (**Fig. 5**).

At the end of the Subboreal period in the Kopanicha section, a significant increase in acid and poor habitats conditions were recorded as well as increase in the role of rainwater (occurrence of *Caricetum lasiocarpae sphagnetosum* phytocoenoses; **Fig. 4**, zone Kop M-6). The presence of *Meesia triquetra*, a brown moss, suggests a minerotrophic habitat while more ombrotrophic taxa like *Sphagnum* were also observed. The frequency and diversity of Cladocera also decreased (**Fig. 3**, subzone KIVc), which indicates that conditions had become unfavourable for Cladocera and suggests continued terrestrialization and acidification. Low water pH is also confirmed by the dominance of *Alona guttata* (**Fig. 3**), which is correlated with slightly pH decrease, and an increase *Sphagnum teres* remains (**Fig. 4**), indicating a change to intermediate trophic conditions (more acid fens and transitional mires). This possibly corresponds to the disappearance of open-water areas in the mire. Between 35 and 12 cm depths, there were no Cladocera remains suggesting a decrease in the water table and the draining of water out of the mire (**Fig. 5**). This period is clearly indicated in the numerical analysis as a single dendrogram branch (**Fig. 3**), and is also confirmed by the depletion of aquatic plant grains, the low percentage of telmatic plants, and the presence of well decomposed peat (**Figs. 2**, **4**, **5**). A gradual decrease in surface wetness in the mire is consistent with both macro- and microfossil assemblages (densification of tree and shrub-cover; **Figs. 4**, **5**). The habitat has become less humid and more oligotrophic, as indicated by the macro- and microfossil records. Thus, the transformation of the mire to transitional peatland was observed (**Fig. 4**, zone Kop M-7).

Subatlantic period (modern time)

The uppermost part of the Kopanicha section (12-0 cm) is likely to have accumulated during the latest Subatlantic period, that is, in modern times (**Fig. 2**, zone Kop5). A hiatus between the upper part of the Subboreal and lower the part of the Subatlantic has been recognized using pollen analysis. In this layer, curves of cereals and other human indicators are present. The presence of *Ambrosia t.* pollen grains suggest that this very thin layer of sediment was accumulated during the 19th century or later

(Podbielkowski 1995). The record of human impact has already been recognized from the Subboreal period (e.g. presence of sporadic grains of cereals) but environmental changes in valley deposits probably do not show marks of human impact (there were no signs of settlement in the vicinity). Only some changes observed in peat composition (namely the increase in ash content and the large degree of decomposition) connected with intensified human activity in Kopanicha have been described (Domińczak and Okupny, 2010) and the changes due to human disturbance on the Rawka River bottom in the last hundred years have also been noted (Kobojek, 2000). At depths of 20-0 cm peat is mucked, so plant macrofossils remains have were not identified.

Three Cladocera species which living among vegetation and tolerating low pH appear here (**Fig. 3**, zone KV). Their presence may be correlated with a wetter conditions induced by higher groundwater level or superficial water input. The presence of *Typha latifolia* grains, the sporadic presence of aquatic plants (**Figs. 2**, **5**), and the low share of telmatic plants confirm these observations on the presence of the water table. Today the site is an alder mire. This period is also clearly marked in the results of numerical analysis as a separate, homogeneous cluster (**Fig. 3**).

5. DISCUSSION: RIVER, CLIMATE, OR LOCAL (AUTOGENIC) CHANGE?

Interdisciplinary palaeoenvironmental studies on the Rawka River valley have demonstrated the main phases of the Holocene (natural and anthropogenic) environmental changes, both on the local and the regional scale. There is a direct (i.e. floods) and indirect (ground waters) relationship between rivers and valley mires. The general results of these interactions are as follows: deposition of mineral-enriched sediments in the mires as a result of flooding, changes in vegetation composition in the mire, changes in the water fauna (Cladocera) as a result of changes in water conditions, changes in the degree of peat decomposition.

We suggest that during most of the history of Kopanicha, the influence of the Rawka River was a very important factor. The location of this mire in river valley suggests that the hydrology of this mire was connected with the hydrology of the drainage basin of the Rawka River. The lower part of the Kopanicha section (oxbow development) was under directly connected with the Rawka by floods, while the upper part was indirectly connected on account of the mire (**Fig. 5**).

At the oxbow stage, these hydrological changes are clearly visible through their effect on the Cladocera and plant assemblages, as well as on the lithological components. Sedimentologically the lower part of the section mainly corresponds to sands. The low frequency of plant-associated Cladocera, the presence of benthic taxa, the increase in soft-bottom dwelling species (e.g. *Pleuroxus uncinatus*), and the appearance of *Bosmina* (*E.*) *coregoni*

may all indicate an increase in the water table consequent on flood events. The composition of Cladocera species – similar to that described in the Warsaw oxbows (Galbarczyk-Gąsiorowska *et al*., 2009) – was interpreted as indicating flood events. Additionally, radiocarbon dates from this part (ca. 8.4-8 ka BP) are broadly consistent with the main phases of increased fluvial activity and higher water level in lakes (**Fig. 6**).

The organic content of oxbow sediments can also have a direct impact on the cladoceran populations (relative decrease value of LOI as a function of increase of organic matter). It is therefore likely that the variations in relative cladoceran abundances are directly related to sedimentary organic matter content and thereby (indirectly) driven by river inundations. Similar phenomena have been observed for chironomid assemblages (Engels *et al*., 2008)

The repeated disappearance of all Cladocera in the Atlantic period may be also related to the flood, and this suggests that at that time, the oxbow (and latter mire) was then flooded, or the Rawka River was flowing (**Fig. 5**). This is confirmed by the presence of fluvial sand sediments, as well by as increases in LOI (**Fig. 5**). Irregular

delivery of allochtonous minerogenic material into lacustrine basins has been described by Brown *et al*. (2000) and Sletten *et al*. (2003), and is either associated with individual river flooding events or else has been interpreted as high-density turbidites attributed to subaerial debris flows plunging into the reservoir. In the Kopanicha situation, most of the flood deposits are fine-grained sediments that settle out of suspension from floodwaters flowing into the oxbow, and sometimes these sediments contain unidentified plant remains as described and recognized in turbid deposits in lacustrine sediments (Sletten *et al*., 2003). To summarize, the flood record in the Kopanicha reservoir is manifested as: (1) relative increases in the number of benthic Cladocera species dwelling on the soft lake bottom, along with the short-lived appearance of a planktonic form; (2) sand admixture in the deposits and increases in the LOI value, and finally (3) a very low frequency or complete lack of pollen, plant macrofossil, and Cladocera remains (**Fig. 5**).

At the mire stage, hydrological changes are clearly visible in their effect on the micro- and macrofossil assemblages, as well as on lithological components, especially from 120 to 80 cm depths. The radiocarbon data (**Table 1**, **Figs. 5, 6**), from a depth of 90 cm (3692-3459 cal BP), 60 cm (3579-3254 cal BP), and partly from 120 cm (4522-3934 cal BP), suggest that this time was connected with an increase in humidity in the mire. This is confirmed by the abundant presence of cladocerans, the increase in their biodiversity, single pollen grains of some aquatic plants, poorly decomposed peat, and the results of plant macrofossils analysis suggesting that at this time that the habitat was permanently and heavily flooded. The value of LOI also increased. We hypothesize that there was an increase in the water table in the Rawka valley as a result of flooding, because this period also corresponds to the main phase of increased fluvial activity (**Fig. 6**), and they are very closely synchronic. Our data allow a good assessment of climatic influence in Poland, from a similar profile and multiproxy approach, because most sites are in the same generally climatic district. But we can only reconstruct the long-term trends of hydrological dynamics, and not their minor fluctuations, on account of the limited available microfossil records from these sites (lack of Cladocera analysis).

The broad patterns of our data, showing an increase in humidity between ca. 4.5-3.9 ka BP and 3.6-3.2 ka BP are consistent with the findings elsewhere in Poland of Ralska-Jasiewiczowa (1987, 1989), Ralska-Jasiewiczowa and Starkel (1988), Starkel (2006) and Żurek and Pazdur (1999) and might further correspond to the succeeding wetter phases recognized in the 4.4-4.1 ka BP and 3.5-2.9 ka BP interval on Polish fluvial, lake and peatland environments. This part of the Subboreal period is considered by Starkel (1990) and Starkel *et al*. (2006) to be a wet period, characterized by more frequent rainy seasons. It is possible that the rise of groundwater levels in the Rawka River valley is associated with this wetter phase
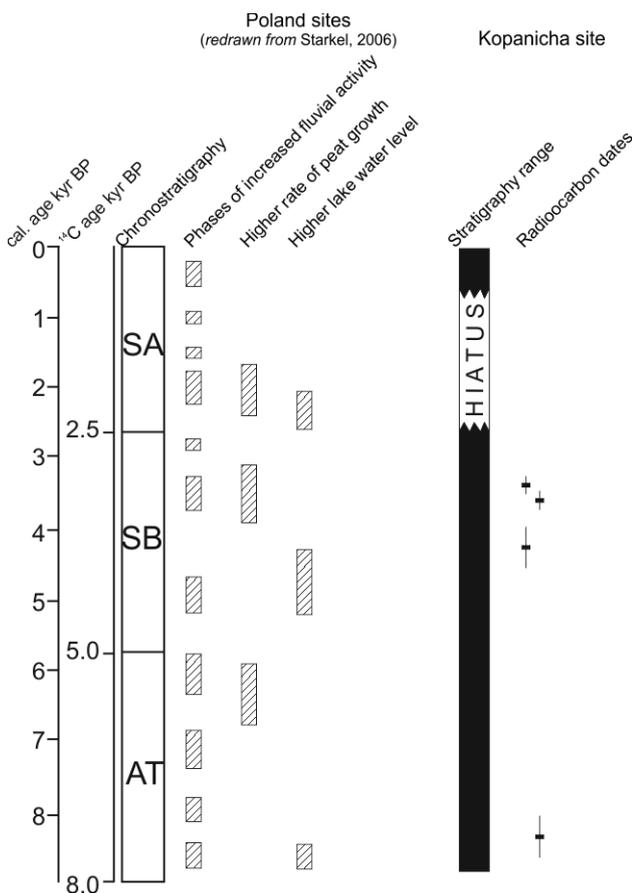

Fig. 6. *Correlation between main phases of increased fluvial activity, higher rate of peat growth and higher water level in lakes in Poland with radiocarbon date from Kopanicha mire.*

of the Subboreal period; our data would seem to agree with this scenario. Similarly, the short-term disappearance of all Cladocera at the end of Atlantic period probably corresponds to the succeeding dry phases recognized at the end of that period (Ralska-Jasiewiczowowa, 1987; Starkel, 1990). Also in the Subboreal period, drier phases have been recognized in Kopanicha mire. The same phenomenon (terrestrialization) has been observed for lakes in Central Europe (e.g. Szeroczyńska and Gąsiorowski, 2002; Gąsiorowski and Kupryjanowicz, 2009). It is possible that locally dryness conditions may have facilitate the colonization of the oxbow by marsh vegetation, and the succession to mire environment. The fact that the mire was located in area of continental climate influences: temperature may be a very significant parameter governing the peatland hydrology (Schoning *et al*., 2005; Charman, 2007). Because wet/dry phases seem consistent within area Poland, we suggest that a global factor, mainly climate, is controlling them.

Although, major changes are replicable, there is often a high level of lower amplitude variability in the peat records, which can be explained by autogenic forcing resulting from internal bog dynamics, actual climatic differences between the locations of different sites, and errors in the derivation of the proxy record (Hendon *et al*., 2001). Therefore, despite the very pronounced influences of river and climate, it is probable that the Kopanicha site has also responded to autogenic factors and local condition changes, especially concerning mire development. One way that this might have occurred is via changes in the structure of the peat, as a feedback effect from changes in the plant community and decay rates (Charman, 2007). As water tables rise and changes in plant species occur together with decreasing decay rates, the hydraulic conductivity of the acrotelm (upper part of peat in which water table fluctuations occur, "living part") peat will change. Longer phases of persistently wet or persistently dry conditions are more likely to lead to turnover in plant species resulting from competition and the build-up of organic matter with different hydraulic conductivity characteristics in the acrotelm (Charman, 2007). However this phenomena mainly occur in Sphagnum dominated bogs and is case for unlikely here.

At Kopanicha mire, which is not dominated by Sphagnum, the second way that local conditions may exert their influence is via changes in the structure of the plant community. The *Alnus* dense (**Figs. 2, 4**) occurring around the Atlantic-Subboreal periods, led to reduced evapotranspiration, and thus favoured the rise of the water table, the development of aquatic fauna and the accumulation of marsh taxa. This situations has already been described on the flood plain (or 'marsh') located in the southwestern Parisian basin (Macaire *et al*., 2006). But these changes ought to be connected with the influence of humans or the climate.

Another possibility is the fact that the mire could have been fed by waters flowing out from the escarpment, if the drainage of the river valley was insufficient to accelerate hydraulic fall. Underground waters (under pressure) and seepage water which might have fed Kopanicha mire (as with other mires in the Rawka valley – see Żurek, 1993), as well as slower run-off, led to higher water tables. As a result, surface conditions became more humid and relatively richer in nutrients at both sites, as indicated by the local plant and cladoceran assemblages.

Ultimately, human impact is unlikely to have been a major factor in affecting mire surface wetness at Kopanicha. Both area in the Rawka River valley show signs that drainage has been minor and mostly peripheral (Kobojek, 2000, 2009). It is possible that Kopanicha has suffered from changes in vegetation composition in the last two hundred years (Kobojek, 2000), which could be attributed to peripheral forestry drainage effects, or to hydrological management. However changes recorded here occurs much earlier than did forestry activity or the known changes in hydrological management.

To conclude the moisture changes, especially in the mire stage were probably controlled by several factors: by river, climate, and to a lower extent, local conditions. Although further research would be needed in order to determine this hypothesis, two of the factors – the influences from climate and from the river – are strong candidates and are currently better supported by the available evidence.

6. CONCLUSIONS

The development of the Kopanicha site began in the Atlantic period. At that time, the site was a part of a palaeochannel of the Rawka River which evolved into a small, shallow oxbow flooded by the Rawka. At the end of the Atlantic and in the Subboreal periods, the reservoir functioned as a mire, firstly as a forest mire, then a sedge mire, and later as a transitional peatland. Nowadays it is an alder mire.

Cladocerans appear to be very useful in reconstructing humidity changes in the mire. Some of them might be correlated with locally prevailing conditions. However, the results presented here represent the first attempt to record the evolution of valley mires as a result of river cycle which is based on an analysis of Cladocera remains.

The transformation from oxbow to mire and the hydrological changes in this reservoir are clearly visible on the micro- and macrofossils assemblages. The record of flood in the Kopanicha reservoir is manifested in: (1) relative increases in the number of benthic Cladocera species dwelling on the soft lake bottom, and the short-lived appearance of a planktonic form; (2) the sand admixture in the deposits (increased value of LOI), and (3) the very low or complete lack of pollen, plant macrofossil and Cladocera remains.

The hydrological regime of the Kopanicha site may have been stimulated by the aggradation and erosion phases of the Rawka River, and was probably caused by

both climatic and local factors. For last several hundred years increased human impact has also had its influences. Most probably, floods were connected with the aggradation cycle of the Rawka River, and in turn, the disappearance of Cladocera probably corresponds to erosion periods of the river, during which the mire was dry as a result of the decrease in groundwater level within the Rawka River valley. During the Subboreal period, a visible groundwater increase manifested as an increase in the frequency of Cladocera, the presence of weakly decomposed peat, and plant macrofossils which living in more humid conditions. It is possible that this time was connected with an increase in humidity in the mire (a rise in the groundwater levels in the valley), and this changes may corresponds to the wetter phases of the Holocene. Our scenario suggests that main drivers are climatic and river influences. Most likely, the autogenic processes and human activities in Kopanicha mire are not major factors which affected the mire surface wetness.

Yet oxbow fills are not the only indicators of large changes in the hydrological regime of rivers (changes of moisture as the result of climate fluctuation). Changes of moisture in Kopanicha mire in the Subboreal and Subatlantic periods best demonstrates this hypothesis, because these situations might be also connected with changes in local conditions. Therefore we should not necessarily expect similar proxy responses over very wide areas.

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