Developmental Changes in the Historical and Present-Day Trophic Status of Brown Water Lakes. Are Humic Water Bodies a Uniform Aquatic Ecosystem?

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Abstract The long-term development of three humic lake ecosystems in Poland was investigated through palaeoecological analyses of sediment cores. These wetland records spanning the Holocene were analyzed for plant macroremains, degree of peat decomposition, sediment geochemistry along with radiocarbon dating. Morphological characteristics of the catchments and data on contemporary water quality and management approaches were integrated. Our research on the palaeoecology of humic lakes suggests two main states: humic and eutrophic-humic. Of the lakes studied, only one consistently presented features typical of the humic type. The other two showed various states, and dynamic patterns of transformation. The results indicate that these systems can change from humic to eutrophic-humic, and back again, in response to catchment-linked factors, climatic change and human impact. Thus determination of uniform pattern in the development of humic lakes is questionable. This suggests that a reassessment of brown water lakes is necessary.

Keywords Humic lake · Sediments · Peat · Subfossil vegetation · Trophy · Catchment

Introduction

Lakes have been classified according to trophic status since the early twentieth century, when clearwater and dystrophic lakes were distinguished (Nauman 1917; Thienemann 1922).

Nauman (1917) singled out dystrophic water bodies as those with *dy* sediments and brown-coloured water. Afterwards these were renamed by Thienemann (1922) as humic lakes. Contrary to clearwater oligo-, meso-, and eutrophic lakes, which can naturally shift from one form to another (Vollenweider 1970; Wetzel 1983), brown water lakes are considered as more uniform. Nevertheless, the origin of both clearwater and humic lakes is usually oligotrophic water in character (Nauman 1919; Davydova and Servant-Vildary 1996).

The terminology related to humic lakes is incongruous and can lead to confusion (Wetzel 1983; Jones 1992), therefore it is essential to develop an unambiguous nomenclature. For example, even the very term dystrophy is controversial, because it suggests only the lack of nutrients in lakes (Hansen 1962), while the lack of nutrients is also linked with a higher amount of humic substances (HS), giving brown water color and low pH (4.0–6.0). The other characteristic features of humic lakes include peat-covered catchment area, sometimes overgrown with coniferous forests, peat mosses in the vicinity of water bodies, spreading floating mats on water surfaces, low water and sediment calcium content, *dy* sediments, small algal biomass, poor taxonomic biodiversity, and higher respiration than primary production (Miles and Brezonik 1981; Salonen et al. 1983; Wetzel 1983; Hessen and Tranvik 1998; Górniak et al. 1999; Brönmark and Hansson 2005; Gąbka and Owsiany 2006; Poniewozik et al. 2011; Rodríguez et al. 2011). Large amounts of humus flow into lakes from catchment basins (De Haan 1992; Hessen 1992), causing water acidification (Kullberg et al. 1993). Organic carbon accretion in humic lake sediments exceeds the areal sequestration rates of soils and forests (Molot and Dillon 1996). The trophic status of humic lakes is determined by vegetation in the catchment and by presence of mires in the vicinity of the lakes. Existence of both the humic lake and the wetland is mutually related and shaped by a complex of biogeochemical processes (Fenner and Freeman 2013). Optimum conditions for forming of these lakes occur in northern regions of the world, with a cool, humid climate

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(Salonen et al. 1983; Kankaala et al. 2006). Among humic lakes those from Northern America and Europe are the most extensively studied featuring in numerous scientific monographs (Hessen and Tranvik 1998; Findlay and Sinsabaugh 2003; Steinberg 2003).

Despite the fact that humic lakes are well described in the literature, most of the research addresses the current status of these water bodies, stressing their hydrobiological, microbiological and ecological problems, like carbon leaching from the catchment and its metabolism in lake (Sachse et al. 2001; Klavins et al. 2003; Taipale et al. 2007), primary production (Jasser 1997; Nürnberg and Show 1998), microbiological utilization of organic matter (Satoh and Abe 1987), and character of vegetation (Catling et al. 1985; Keskitalo et al. 1998). Less attention was paid to historical development of humic lakes. Characteristically, they have been described by some authors as minimally changeable in time (Więckowski 1978; Górniak 1996). On the other hand, humic lakes are considered to be sensitive to environmental disturbances (Curtis 1998), which are especially important in an era of progressive climatic, anthropogenic, hydrometeorological, and ecological changes. In this situation a question is how much sensitive they are.

Climate change models predict that higher temperatures are likely to occur over most of the boreal forests in North America, Europe, and Asia (Porcal et al. 2009) which can cause modifications in habitats making them less favorable for dystrophy and leading to disappearance of humic lakes. Simultaneously, over the past few decades, phenomena that are advantageous for the formation of humic lakes have been observed; namely, the intense export of organic matter to surface waters (Freeman et al. 2001; Roulet and Moore 2006; Evans et al. 2012).

As changes in character of humic lakes are observed now, it is most probable that these water bodies were changing also in the past. In our studies we used palaeobotanical and chemical sediment analyses combined with analyses of current water quality to describe the development of three humic lakes. This made possible to verify views on the functioning of this type of ecosystems. Subfossil plant remains, preserved very well in mires due to their anoxic conditions, render it possible to describe histories spanning thousands of years in lakes surrounded by mires. No such possibility exists for the vicinity of clearwater lakes. One of the most meaningful parameters is sediment C/N ratio which allowed determining the sources of organic matter in sediments (autogenic or allogenic).

The aims of the study were: (i) to reconstruct the lakeside vegetation and habitat conditions in the vicinity of the studied water bodies; (ii) to determine whether or not different types of humic lakes occur; (iii) to identify developmental tendencies of humic lakes. Our findings were then used to verify the hypothesis that humic lakes are not uniform ecosystems and can change over time.

Methods

Study Site and Field Work

Wigry National Park (WNP) is located in NE Poland (Fig. 1). Two physical-geographical mesoregions—the East Suwałki Lakeland and the Augustów Upland, occur in this part of Poland, and both are included in the Lithuanian Lakeland (Kondracki 1994). The terrain of this area was shaped during the Pomeranian phase of the main stadial of the Weichselian (Vistulian) Glaciation (Marks 2002). A number of kames, eskers, and frontal moraine heights occur in the northern and middle parts of WNP, while the southern part of the park comprises an extensive sandur with strongly transformed primary glacial relief (Ber 2009). The climate of this area is temperate, transitional between maritime and continental with a tendency toward continentality. Climatic conditions and vegetation cover liken this territory to Scandinavia.

The humic lakes of the WNP are located in the vicinity of the Wigry Lake, one of the biggest and deepest lakes in Poland (area 21.63 km², max depth 74.2 m). Lake Suchar IV (SIV in following text) and Lake Wądołek (Wd in following text) are located to the north of Lake Wigry, and Lake Sucharek (Sch in following text) is situated on the southern shores of Lake Wigry (Fig. 1). Studied lakes are characterized by different morphological parameters of lake basin and character of catchment (Table 1).

Material for the study was collected from the lakesides of three dystrophic lakes, using a Russian sampler (50 cm long and 8 cm in diameter). The lengths of the cores were as follow: from SIV—370 cm, from Wd—240 cm, and from Sch—170 cm. The cores were divided into segments of 5 cm.

Laboratory Analyses

Macroscopic plant remains analysis was the main method of research. Distilled water with an addition of 10 % KOH, was used to soak the material. Next, the suspensions were boiled, rinsed in a 0.2 mm sieve, and placed in Petri dishes. At first, generative finds (fruits, seeds, fruit scales) from every sample were picked out. These finds were identified using a stereoscopic binocular microscope (Nikon SMZ 800) at magnification of 10–63×. Vegetative plant remains (roots, epiderm, periderm, rhizoderm, leaves, stems, and wood) were identified using a Leica DM 3000 light microscope with 200–400× magnification. Botanical composition, based on a proportion of each taxon tissues in total tissue mass, was estimated. Only remains with cellular structures were taken into account. Remains were identified with help of Mauquoy and van Geel (2007), Hedenäs (2003), Katz et al. (1965), and the collection of macroscopic plant remains at the Institute of Biology, University of Białystok. Countable remains (for example, seeds) were presented at absolute sums. Diagrams of vegetative

Fig. 1 The location of study lakes in the Wigry National Park (NE Poland)

macrofossils were based on percentage data. Peat units were distinguished according to Tolpa et al. (1967). In *dy* samples presence of remains was recorded.

The next method was the microscopic analysis of the degree of peat decomposition. This analysis is based on the humus/peat ratio in the sample. According to Obidowicz (1990), peat may be divided into: slightly decomposed (decomposition up to 25 %), medium decomposed (30–40 %), highly decomposed (45–60 %) and humopeat (65 % and up).

This parameter delivers information about humidity of the mire surface during the past peat forming process. A decrease in the degree of peat decomposition indicates a ground water table rise.

The results were presented as diagrams drawn with the computer program POLPAL (Walanus and Nalepka 1999). Plant macrofossil zones were distinguished (Figs. 2, 3 and 4). They illustrate various stages of vegetation succession and deliver information about palaeoenvironmental changes in the nearest surroundings of the studied humic lakes.

Table 1 Location and parameters of studied lakes (acc. to Górniak (2006))

Lake	Latitude	Longitude	Area (ha)	Max. depth (m)	Shoreline development index	Catchment (ha)	Catchment/lake area ratio	Catchment character	Catchment slope (‰)
Suchar IV	54°05'22" N	23°01'29" E	0.95	8.0	1.59	68.7	72.31	Forested	62
Wądołek	54°06'39" N	23°02'37" E	1.09	15.0	1.28	19.4	17.79	Arable-forested	73
Sucharek	54°00'44" N	23°07'13" E	0.63	6.0	1.40	22.6	35.87	Pasture-arable	30

Fig. 2 Lake Suchar IV. Diagram of the macroscopic plant remains, decomposition degree of peat and chemical parameters of sediments. **a** vegetative remains, **b** generative remains, **c** other remains. Solid line corresponds to TKN, dashed line—to C, dotted line—to C/N

^{14}C samples were prepared by manual selection of plant remains according to Kilian et al. (2000) and dated in the Poznań Radiocarbon Laboratory (Poznań, Poland; Poz), in the Gliwice Radiocarbon Laboratory (Gliwice, Poland; GdA), and in Laboratorium Datowań Bezwzględnych (Skala, Poland; MKL). The radiocarbon age of the samples was calibrated with CalPal 1.5 ver. online software (Danzeglocke et al. 2011) and with OxCal 4.1 online software (Bronk Ramsey 2009). The chronology of the peat profiles was presented according to Mangerud et al. (1974), with calibration of chronozone boundaries (Walanus and Nalepka 2010). The radiocarbon dates are given in detail on Table 2.

The chemical analyses of sediments were based on the quantification of organic carbon content, total Kjeldahl nitrogen (TKN), and on estimation of C/N ratio. Sediment samples were dried at 105 °C after removal of all particulate organic matter greater than 1 cm in length. For further analyses the sediments were ground to break apart aggregates. Samples were tested for carbonates by treating with 10 % HCl and observing effervescence. Total organic carbon (C) was determined by incineration of the samples in 550 °C for 5 h in a common furnace (Howard and Howard 1990). Total Kjeldahl nitrogen was determined on 0.25–1.0 g of dry sediment samples according to Bremner and Mulvaney (1982). Organic C and total Kjeldahl N values were

corrected to air-dry weight. Lake water pH was measured using a portable device (Jenway 370 pH Meter).

Results

The sediment thickness and typologies differed among the cores analyzed. Most of the peat material was comprised of vegetation remains such as vascular plant tissues, leaves, branches, and moss stems. Fruits and seeds were noted sporadically. Aquatic remains such as astroscleroids of Nymphaeaceae and Cladocera and Chironomidae remains were also noted. The deepest sediment samples comprised a peat layer mixed with sand (Figs. 2, 3 and 4).

The two peat units identified in the SIV profile were *Sphagnum* peat, and *Sphagnum* peat with *Pinus*. The peat is moderately and strongly decomposed (Fig. 2). Three macrofossil zones were identified (Fig. 2). In the SIV-1 zone periderm of *Pinus sylvestris*, *Alnus* and *Betula* is recorded (max. 5–10 %). Remains of peat mosses, epiderm of Poaceae, roots of Ericaceae, and epiderm of *Phragmites australis* are noted in minimal amount. In the SIV-2 zone remains of *Sphagnum magellanicum* comprise even 75 % of the sediment volume. Periderm and needles of *Pinus*

sylvestris reaches 30 %. The last zone (SIV-3) is characterized by the domination of *Sphagnum magellanicum* (max. 80 %). The presence of *Pinus sylvestris*, Ericaceae, *Sphagnum fallax*, *Sphagnum angustifolium*, *Pleurozium schreberi*, and *Carex cf. limosa* is recorded.

Sphagnum peat and *Carex-Sphagnum* peat were noted in the Wd profile, and the degree of the decomposition of the peat was more varied than that in the SIV profile (Fig. 3). Two macrofossil zones were identified (Fig. 3). In the Wd-1 zone vascular plants are represented by radicles of *Carex cf. limosa*

Fig. 4 Lake Sucharek. Diagram of the macroscopic plant remains, decomposition degree of peat and chemical parameters of sediments. **a** vegetative remains, **b** generative remains, **c** other remains. Solid line corresponds to TKN, dashed line—to C, dotted line—to C/N

Table 2 Radiocarbon datings from studied profiles

Core	Sample depth (cm)	Sample composition	Laboratory number	Conv. ^{14}C age	Cal. year acc. to CalPal 1.5 (Danzeglocke et al. 2011) 68 % probability ¹ and acc. to OxCal 4.1 (Bronk Ramsey 2009) 95 % probability ²
Sch	29	Stems of peat mosses	MKL-1796	2,620±70 BP	2,800–2,580 BP ¹
	68	Leaf epiderm of common reed	MKL-1797	7,580±80 BP	8,400–8,300 BP ¹
	169	Leaf epiderm of common reed	Poz-30005	8,765±50 BP	9,880–9,670 BP ¹
Wd	239	Leaf epiderm of common reed, stems of mosses	Poz-38255	6,250±40 BP	7,230–7,100 BP ¹
	153	Stems of peat mosses	GdA-2382	101.29±0.23 pMC ^a	1,953–1,956 AD ²
SIV	191	Stems of peat mosses	MKL-1793	800±100 BP	1,020–1,390 AD ²
	255	Stems of peat mosses	MKL-1794	1,210±70 BP	670–980 AD ²
	369	Stems of peat mosses, grass epiderm	Poz-8253	4,405±35 BP	5,000–4,900 BP ¹

^a The date is modern (pMC percent modern carbon)

(max. 20 %), seeds and rhizome epiderm of *Menyanthes trifoliata*, roots of Ericaceae, wood of coniferous and deciduous trees/shrubs. Mosses, like *Sphagnum cuspidatum*, *Sphagnum fallax*, *Straminergon stramineum*, *Pleurozium schreberi*, and *Polytrichum commune* are present. The last zone (Wd-2) is characterized by the dominance of *Shagnum magellanicum* (max. 90 %). *Sphagnum fallax* comprise even 30 %.

The three peat units described in the Sch profile were Cariceto-Phragmiteti peat, Cariceto-Phragmiteti peat with wood, and *Carex-Sphagnum* peat. This peat is slightly, moderately, and strongly decomposed (Fig. 4). Three macrofossil zones were noted (Fig. 4). The oldest zone (Sch-1) is characterized by the dominance of *Carex* radicles (max. 40 % in sample), and remains of *Phragmites australis* (max. 50 %). *Carex* cf. *elata* comprises even 25 % of the sediment volume. In the Sch-2 zone radicles of *Carex*, *Carex* cf. *rostrata* and remains of *Phragmites australis*

dominate achieving 35%, 20% and 25%, respectively. A distinct amount of coniferous wood is noted (max. 25 %). The top zone (Sch-3) is characterized by the dominance of *Carex* remains (max. 25 %), and *Carex* cf. *limosa* radicles (even 30 %). *Sphagnum fallax*, *Sphagnum cuspidatum*, species of the *Acutifolia* section, *Polytrichum commune*, *Scheuchzeria palustris*, and *Menyanthes trifoliata* are recorded.

The highest content of organic carbon was noted in the *dy* sediment from SIV, where it exceeded 54 % (Fig. 2; Table 3), while the lowest (approximately 40 %) was noted in the *Carex-Sphagnum* peat in Wd (Fig. 3; Table 3). The TKN content ranged from more than 2 % in *dy* sediment from SIV (Fig. 2; Table 3) to more than 1 % in *Sphagnum* peat from Wd (Fig. 3; Table 3). The highest C/N ratio (approximately 45) was noted in *Sphagnum* peat from Wd (Fig. 3; Table 3), while the lowest of less than 20 was noted in *dy* samples from SIV (Fig. 2; Table 3). The values of

Table 3 Typology and chemical parameters of sediments

Profile	Depth (cm)	Sediment	Mean C (%)	Mean TKN (%)	Mean C/N	Number of samples
SIV	100–250	<i>Sphagnum</i> peat	53.61	2.27	24.73	20
	250–310	<i>dy</i>	54.28	2.71	19.99	12
	310–360	<i>Sphagnum</i> peat with <i>Pinus</i>	42.53	1.74	24.32	10
	100–360		50.14	2.24	23.01	42
Wd	0–160	<i>Sphagnum</i> peat	53.45	1.21	45.36	32
	160–230	<i>Carex-Sphagnum</i> peat	40.07	1.51	25.59	14
	0–230		46.76	1.36	35.47	46
Sch	0–30	<i>Carex-Sphagnum</i> peat	43.80	1.36	31.53	6
	30–70	Cariceto-Phragmiteti with wood	48.65	1.31	37.89	8
	70–160	Cariceto-Phragmiteti	52.02	2.54	22.57	18
	0–160		48.15	1.67	30.66	32

the chemical parameters of the Sch sediments were intermediate (Fig. 4; Table 3). The lake water pH in 2011 was: SIV—4.3, Wd—5.8, and Sch—5.5.

The peat-forming processes in the studied lakesides began in different periods of the Holocene. The age of bottom sediments was 5,000–4,900 cal. BP in SIV, 7,230–7,100 cal. BP in Wd, and 9,880–9,670 cal. BP in Sch. The peat moss floating mat of Lake Suchar IV occurred after 670–980 AD, and its presence was confirmed by dating 1020–1390 AD (Fig. 2). In the Wd lakeside bog started to exist about six decades ago (1953–1956 AD) (Fig. 3). In the vicinity of Sch reedswamp vegetation occurred in the Boreal and Atlantic periods. Pine admixture was noted after 8,400–8,300 cal. BP. Sedge-peat moss floating mat started to exist 2,800–2,580 cal. BP (Fig. 4).

The subfossil plant community succession differed in each of the lake shores studied. A rich fen vegetation was only noted in the Sch mire, while that at the Wd and Sch sites comprised moderately poor fen vegetation. The bog phase was noted at SIV and Wd. The following sequences of subfossil vegetation were identified:

- SIV shrub communities of fen? (SIV-1 zone)→peat moss communities of bog (SIV-2, and SIV-3 zones)
- Wd communities of moderately poor fen (Wd-1 zone)→peat moss communities of bog (Wd-2 zone)
- Sch reedswamp vegetation of rich fen (Sch-1, and Sch-2 zones)→communities of moderately poor fen (Sch-3 zone)

Discussion

All three of the lakes studied have brown waters, but they differ distinctly. Lake Suchar IV exhibited, and still exhibits today, the features of a typical humic lake. Lakes Sucharek and Wądołek should, in light of their past and present qualities, be classified as atypical humic lakes that are on the cusp between dystrophic and eutrophic (Nürnberg and Show 1998). This also means that these lakes can be classified as alloiotrophic (Wetzel 1983), mixotrophic (Williamson and Morris 1999), or humoeutrophic lakes (Górniak 2006; Chmiel 2009; Zieliński et al. 2011). In Estonia, Sweden, and Finland, lakes called dystrophic (humic), semidystrophic, and dyseutrophic are identified (Arst and Reinart 2009). Klavins et al. (2003) describe some Latvian lakes as dystrophic and dyseutrophic, with the latter characterized by higher pH values.

Lake Suchar IV

The peat-forming process at the Lake Suchar IV lakeside began in the first half of the Subboreal period (5,000–4,900 cal. BP), and was initiated by shrub communities of birch, alder, and pine (SIV-1) (Fig. 2). The occurrence of shrubs could have resulted from strong surface flow caused by heavy rainfall, what was

observed for example by Oświt (1977) in his wetland studies in northeastern Poland. During this part of the Subboreal period, heavy rainfall was noted throughout investigated region (Ralska-Jasiewiczowa and Starkel 1988).

A floating mat comprised primarily of *Sphagnum magellanicum* (SIV-2 and SIV-3; Fig. 2) was dominant during the development of the mire. *Rhynchospora alba*, present there, is also representative of low nutrient habitats (Zarzycki et al. 2002), linked to mire pools; the mean height of which appears to be 12–14 cm above the water table (Mauquoy and van Geel 2007). The floating mat (SIV-3) occurred after 670–980 AD (Fig. 2).

The studied profile reflects distinct changes in hydrometeorological conditions that are representative of this region in the past, and as a result of which both *dy* sediments and peat accumulated. The peat is moderately and strongly decomposed (Fig. 2), which could have resulted from fluctuations in water levels. However, the occurrence of *dy* indicates, according to some authors, that the water quality conditions of the lake waters are minimally variable (Więckowski 1978; Górniak 1996). Water gaps (Fig. 2) probably occurred as the result of later water level increases, because they are not a consistent part of the mire (Kowalewski and Barabach 2010).

High TKN content in sediments evidences strong impact of lacustrine ecosystem on the biogeochemistry of the SIV core (Fig. 2; Table 3). Organic matter of lacustrine origin is a source of nitrogen, and the sediments from the SIV core have abundant cladoceran remains, Nymphaeaceae tissues, and Chironomidae larval mouth parts as are reflected in the C/N ratio values. The C/N parameter is used to determine the domination of autogenic or allogenic sources of organic matter in sediments. The C/N ratio for aquatic plants, phytoplankton, and zooplankton is 10 or below, whereas that for terrestrial plants exceeds 10 and can be as high as 45–50 (Meyers 1994; Ji et al. 2005). Algae, phytoplankton, and zooplankton contain large amounts of protein, hence the C/N ratio is lower (Krishnamurthy et al. 1986). The sediments from the SIV core include a distinct admixture of autogenic organic matter, which could explain why these sediments had the highest content of nitrogen and the lowest of C/N (Fig. 2; Table 3).

Based on the data presented above, Lake Suchar IV can be classified as a typical humic lake. The substantial impact on its trophic state had also location within a forested catchment area that is large in terms of closed systems (Table 1). The sediment profile studied indicates that the character of this lake did not change for a thousand years. The pine forests covering the area surrounding the lake contribute large quantities of HS (Górniak and Zieliński 2000; Hagedorn et al. 2000), which have and presently continue to reach this lake. Lake Suchar IV has the highest catchment/lake area ratio among the three lakes studied, which is advantageous (for example, Curtis and Schindler 1997), and it also has the highest shoreline development index (Table 1). This indicator describes how the coastline is similar to a circle. A bigger number means that shoreline is more varied and that the

interface between the water and the surrounding land is more significant (Moses et al. 2011). Both subfossil and contemporary vegetation are typical of humic lakes, while the floating mat comprises two well-developed zones—quaking and firm.

The trophic state of lakes can be determined using the Hydrochemical Dystrophy Index (HDI) described by Górniak (2006). The values of this parameter range from several points for clearwater lakes to more than a hundred for humic lakes. The HDI value of 50 is the minimal values for humic lake classification. The HDI value noted in 2002 for Lake Suchar IV was 104.2, which means that this parameter was more than twofold than the minimal value for humic lakes.

A low chlorophyll a concentration (14.05 µg/l) and the highest DOC content were also noted (39 mg/l), which is evidence of high HS levels (Górniak 2006). DOC is known to be the principle controlling factor of acidity in humus-rich brown water lakes (Kullberg et al. 1993). Water pH fluctuated from 3.8 to 6.0 in the 1971–2002 period, but the value of this parameter always indicated strongly acidic conditions, which was confirmed by the pH value of 4.3 in 2011.

Lake Wądołek

Peat accumulation began in the lakeside of Lake Wądołek in the middle of the Atlantic period (7,230–7,100 cal. BP), when rainfall was heavy in the region that is present-day Poland (Ralska-Jasiewiczowa and Starkel 1988). This supported species that tolerate ombrotrophy such as *Sphagnum cuspidatum*, *Sphagnum fallax*, *Straminergon stramineum*, and *Carex limosa* (Wd-1) (Fig. 3). Conditions in the bog-surface pools were suboptimal for *S. cuspidatum* (Boatman 1977), while *S. fallax* is often associated with habitats with high humic substance concentrations (Gąbka and Lamentowicz 2008). *Straminergon stramineum* is typical of moderately rich fens, but is also noted in both rich and poor fens (Hájek et al. 2006). *Carex limosa* occurs on poor and moderately poor, and acidic and moderately acidic substratum (Zarzycki et al. 2002). Hence, the Lake Wądołek lakeside was likely a moderately poor fen.

Sphagnum magellanicum dominated (Wd-2) the next phase of mire development (Fig. 3). Decreased ground water levels caused the mire to transform into a bog (1953–1956 AD) supplied by heavy precipitation, which is reflected in the predominance of slightly decomposed peat (Fig. 3). *S. fallax*, ericaceous dwarf shrubs, and *Eriophorum vaginatum* are evidence of poor habitats. The latter of these species is typical of extremely poor, highly acidic soils (Zarzycki et al. 2002) in which TKN contents and C/N ratios exhibit values typical of raised bog peat (Damman 1988) (Table 3).

Based on palaeobotanical analyses, a typical humic phase was identified in the past of Lake Wądołek. Its catchment area was probably forested, which resulted in higher inputs of HS into this lake. Currently, the catchment area is a combination of arable and forested lands (Table 1), where the former comprises

about a third of the area. However, the domination of forests is not reflected in the intense DOC supply. This could be explained by the steep slopes of the catchment area (Table 1) which are not advantageous for the accumulation of soil organic matter (for example, Rasmussen et al. 1989). Consequently, dissolved organic matter export from the catchment area was probably much lower than expected, and the DOC content in Lake Wądołek is lower than that in the two other lakes studied (18 mg/l; Górniak 2006). The HDI was only 59.8 in 2002, and, according to Chmiel (2009), when this parameter oscillates around 50, the lake cannot be classified as humic. Moreover, the value of this index fluctuated periodically, which was also noted in a few other lakes in southeastern Poland. The mean pH value noted in 1986–2002 was high at 6.8 (Górniak 2006), and it was 5.8 in 2011. Additionally, the floating mat is atypical: the first zone is fragmentary, with reedswamp species, and the second zone is absent.

Lake Sucharek

Decreasing water level in Lake Sucharek was noted at the beginning of the Boreal period (9,880–9,670 cal. BP), when lake and mire water level declined in studied region of Poland (Ralska-Jasiewiczowa and Starkel 1988) and also in mid-European lakes (Magny 2004). Thus, macrophytes could have grown in shallow littoral waters, including species such as *Phragmites australis* (Björk 2010) that indicates water depths of less than 1 m, which is optimum for this species (Hannon and Gaillard 1997). Tall sedges, like *Carex elata*, *Carex rostrata*, and *Carex pseudocyperus*, as well as *Equisetum limosum*, *Thelypteris palustris*, and *Typha* were present in the lakeside (zones Sch-1 and Sch-2; Fig. 4). Thus, reedswamp vegetation typical of rich fens was present in the Boreal and Atlantic periods, at least, then with pine admixture (see dating 8,400–8,300 cal. BP; Fig. 4). Peat formed beneath the emergent macrophytes from their roots, rhizomes, and leaf bases (for example, Rydin and Jeglum 2008). High values of C/N in the Cariceto-Phragmiteti peat (Table 3) could be explained by higher carbon contents in samples with coniferous wood, which were followed by large amounts of lignin (for example, Lamblom and Savidge 2003).

S. cuspidatum and *S. fallax* occurred in the decline of the Subboreal period (2,800–2,580 cal. BP), in the last stage of mire development (Sch-3) (Fig. 4), and other taxa associated with bogs and poor fens were also noted, including *Carex limosa* and *Scheuchzeria palustris*, which occur in poor and moderately poor, acidic and moderately acidic substratum (Zarzycki et al. 2002). The last phase of mire development (Sch-3) was characterized by the disappearance of *Phragmites australis*, *Equisetum limosum*, and tall sedges. A moderately poor fen formed, and the water level probably did not increase because deciduous trees/shrubs appeared at the mire. Reedswamp vegetation was probably eliminated because of

changes in the nutrient loads from the catchment area. Strongly decomposed peat at the top could have resulted because of low water level in the lake.

The history of this lake differed from those of the other two lakes studied. Palaeobotanical evidence suggests that Lake Sucharek developed both as a humic lake with signs of eutrophication, and a typical humic lake. The former type of lake formed under the influence of its surroundings that were overgrown by reedswamp vegetation, and a catchment area that was probably not significantly forested. The latter lake type had plant communities linked to moderately poor fens. The HS supply to the lake was probably high at that time, which could have been linked to the extension of pine forest area in the catchment as a result of tree planting following World War II (through the analysis of topographical maps). That is why Lake Sucharek currently resembles contemporary humic lakes, such as Lake Suchar IV.

Some circumstances, however, could portend changes in the near future. The HDI was 82.1 in 2002, which is an intermediate value, whereas high chlorophyll *a* levels indicate higher trophic levels. Górniak (2006) reported that the mean pH value from 1994 to 2002 was 6.1, with an extremely high value of 8.1 noted in 1994. Only in 2011 was pH 5.5. DOC content of 28 mg/l was lower than that in the typically humic Lake Suchar IV. The arable and pasture character of the catchment area plays a significant role in shaping the state of this lake (Table 1).

Problem of Humic Lakes Uniformity

The terminology for humic lakes must be unified. Already previously there was an assumption that these lakes are not uniform (Drzymulska et al. 2013). In the current study we indicate a need to distinguish the different states of the humic lakes. It was decided that beside typical humic lakes, those exhibiting signs of eutrophication should be referred to as eutrophic-humic lakes. Based on their history from palaeobotanical data, sediment analyses, and current hydrochemical parameters, the following sequences of lake development were identified:

- SIV humic lake (SIV-1, SIV-2, SIV-3, and present)
- Wd humic lake (Wd-1, and Wd-2)→eutrophic-humic lake? (present)
- Sch eutrophic-humic lake (Sch-1, and Sch-2)→humic lake? (Sch-3)→eutrophic-humic lake? (present)

Thus, like clearwater lakes, humic lakes undergo transformation, which confirms the hypothesis of the current study. Usually humic lakes show an oligotrophic phase (OL) in the beginning of their development. However, it is impossible to designate any uniform pattern in the

development of brown water lakes because of the complexity of the lake-catchment system. Nonetheless, the transition from a typical humic state (TH) to a eutrophic-humic state (EH) appears to be plausible, as does the reverse:

OL→TH↔EH

Our studies demonstrate the lack of uniformity in the developmental history of these three humic lakes and it is therefore vital that further research is conducted in order to recognize the different states of these brown water ecosystems. This will require enhanced investigations of the complex lake-wetland relationships.

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