

Current state and vegetation history of spring-fed fens in Western Pomerania (Northern Poland): a case study of the Chociel River valley

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Abstract Alkaline spring-fed fens are a rare type of soligeneous wetlands, characterised by an alternating arrangement of layers of peat and calcareous tufa, defined as the peat-tufa rhythmite. They are known, for example, from the strongly undulating young glacial landscapes of Central Europe, where many of them are protected by law. These include sites located in the Chociel River valley, in Western Pomerania (Northern Poland). One such spring-fed fen (Bobolice site) was investigated in detail using multiple methods (phytosociological, plant macrofossils, sedimentological and geochemical) for the current state of vegetation, reconstruction of its long-term development and, eventually, the identification of management

strategies for its effective protection. Six developmental phases reflecting changes in the natural environment at the end of the Late Glacial and in the Holocene, as well as changes caused by human impacts in recent centuries, were identified for the investigated site. In the past, the dominant role in the formation of the spring-fed fen was attributed to sedge and sedge-moss communities, also with an admixture of *Sphagnum* in the last phase of the fen's development. For about 300 years increased human activity has been recorded in the Chociel Valley, resulting in a modification of the water regime and a strong transformation of vegetation. Today, the real vegetation is therefore the result of both the presence of various mire habitats and various types of agricultural use. The current state of spring-fed fens in the Chociel River valley points to the urgent need for the implementation of various active protection measures.

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Introduction

Alkaline spring-fed fens belong to the rare group of fens supplied by confined groundwater rich in calcium carbonate (Fairfax and Fensham 2003). The most important feature of these habitats is the precipitation

of calcium carbonate in the groundwater discharge zone. This, in turn, determines the low content of organic matter in the deposition bed, which is usually ca. 5% (Hájek et al. 2002). However, the rate of CaCO_3 deposition can vary even within one season (Komor 1994) and also between day and night (Pentecost 2005). A characteristic feature of this type of site has been observed by several authors (Succow and Joosten 2001; Miner and Ketterling 2003; Dobrowolski et al. 2005, 2016; Mazurek et al. 2014), which is the alternating arrangement of layers of peat and calcareous tufa, with clearly marked cycles of deposition. Dobrowolski (2011) defines this type of deposit as the peat-tufa rhythmite and links it with a change in water supply conditions, which usually corresponded with changes in humidity and temperature during the Holocene.

A specific type of supply of alkaline spring-fed fens and, associated with it, tufa deposition determines the occurrence of large numbers of basiphilous fen species (Grootjans et al. 2006). Large numbers of specific plant and animal species recorded in such habitats (Wassen et al. 2005) is also an effect of low availability of nutrients, caused by the co-precipitation of phosphorus with iron hydroxides or calcite (Rozbrojová and Hájek 2008). Together with other fen types, such as rich and poor fens, alkaline fens are among the most floristically diverse of all wetland types, supporting a large number of rare bryophytes and vascular plant species, as well as uncommon animals (Hájková and Hájek 2003).

Because of the continuous peat-tufa record of carbonate-biogenic deposition, these beds are excellent for detailed palaeoenvironmental studies (Dobrowolski et al. 2002, 2005, 2012, 2016; Alexandrowicz 2013; Mazurek et al. 2014; Pietruczuk et al. 2018). One of the possible methods used for this purpose is the analysis of plant macrofossils, which allows for the reconstruction of subfossil vegetation, identification of its succession sequences, and reconstruction of the past environmental conditions. This method works well for peat (analysis of both vegetative and carpological remains) and lake sediments (carpological finds). Such analyses can also be performed for samples of calcareous tufa, although this is not a standard procedure. The main difficulty concerns the strong fragmentation of plant tissues, which is reflected in the significant proportion of unidentified remains. This is probably one reason for

which analyses of plant macrofossils in deposits of calcareous tufa are known only from a few sites, mainly from the Carpathians (Grootjans et al. 2005; Rybníčková et al. 2005; Hájková et al. 2012), and recently also from the Eastern European lowlands (Dobrowolski et al. 2012; Apolinarska and Gałka 2017) and calcareous uplands in eastern Poland (Dobrowolski et al. 2016; Pietruczuk et al. 2018). These methods are omitted, and malacological analysis (Ložek 1964; Alexandrowicz 2004; Horsák and Hájková 2005), or less often palynological analysis are done instead (Jankovská 1988; Pidek et al. 2012).

Spring-fed fens are known mainly from the temperate zone of the Northern Hemisphere. However, they are critically endangered, mostly due to drainage in surrounding areas, eutrophication, or land use changes (Hájek et al. 2002; Bedford and Godwin 2003; Grootjans et al. 2006; Middleton et al. 2006). Both forestation and deforestation, and also agricultural activities in the catchment area are closely related to CaCO_3 precipitation in calcareous fens. At many Central-European locations, the onset of CaCO_3 deposition has been shown to coincide with settlement and deforestation (Hájková et al. 2012), as well as with moistening of climate (Hájek et al. 2016; Šolcová et al. 2018). Because of the unique nature of spring-fed fens, both from the point of view of the contemporary values of these ecosystems and their significant paleoecological value, preserving still existing and untouched calcareous mires should have priority. This is even more important because it is difficult or even impossible to restore a once degraded calcareous spring system to its original state of calcite deposition and associated vegetation when groundwater flow paths are altered (Grootjans et al. 2015).

One particularly important document for the protection of spring mires in the context of European Union legislation is Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora, which obliges member states to preserve all of the Natura 2000 habitats, including phytocoenoses classified as the *Cratoneurion commutati* alliance (code 7210) and habitats of alkaline fens (code 7230). Spring mires are among the most valuable and the most interesting habitats in the ecological aspect, and also the most difficult to protect mire ecosystems. Their existence depends on specific hydrogeological conditions, which can only slightly

be influenced by humans when planning active protection measures.

Spring-fed fens are also the poorest investigated group of wetland ecosystems of Northern Poland. Most of them are found in contact zones of geomorphological units with a different geological structure, usually in areas with significant hypsometric gradients. Among the privileged areas in terms of quantity and discharge of outflows are valleys and fluvio-glacial plains with a river terrace system, sections of the Pomeranian marginal spillways, and subglacial-trough and ravined valleys. Deep incisions of the valleys and high hydraulic gradients create beneficial conditions for groundwater drainage of local and regional range from the recharge areas, i.e. surrounding morainic plateau levels and fluvio-glacial plains (Mazurek 2010).

A particularly high number of valuable spring mires are found in Western Pomerania. Some of them are transformed, to different degrees, by human activity. In the past, they were drained, some were partially exploited, and most of the sites were mown or grazed. For this reason, local conditions have to be investigated in detail using multiple research methods (including ecological and paleoecological methods) to establish specific measures for the protection of individual sites. Therefore, the main aims of our study were: (i) identification of the current state of spring-fed fen in Western Pomerania, (ii) identification of contemporary plant cover and human impact, and, for the most valuable site from this group of alkaline fens (Bobolice site case study), also (iii) reconstruction of past vegetation and its successive directions (natural and anthropogenically induced). For a more comprehensive assessment of connections between ecological succession and contemporary state of vegetation of alkaline fens in the Chociel River valley we used also the partly published results of our previous studies (Mazurek et al. 2014).

We assume that only a full understanding of the conditions for the development of this type of site in the past allows for their relevant protection at the present time, and also offers the opportunity to predict future events related to climate change and progressing anthropogenic pressure.

Study site

The study site is located in the Chociel River valley (Parșeta River catchment), in the Western Pomeranian Lake District (Fig. 1A, B), whose land relief, geological structure and hydrographic network were formed during the retreat of the ice sheet of the Pomeranian phase of the Weichselian. This area is characterized by significant hypsometric differences associated with postglacial and fluvial land forms and the presence of a thick, up to 200 m, layer of glacial deposits (Fig. 1C).

Spring mires in the Bobolice site are located within a vast complex of mires (ca. 200 ha; see Osadowski and Wolejko 1997). There are over ten spring mires, situated at the bottom of the Chociel River valley and on the valley slopes (Fig. 1D, E). For detailed ecological and paleoecological analyses we selected a cupola spring mire in the central part of the valley, coded BOB (area 1386 m²; relative elevation 1.45 m; Fig. 1E).

The Chociel River valley uses a deep subglacial channel (depth 30–40 m), which cuts through the undulating morainic plateau, composed of glacial sands, locally overlying tills. The deep incision of the valley, and in effect its high hydraulic gradients, create favourable conditions for the drainage of groundwater from the surrounding morainic plateaux that are its alimentation areas. The discharge in the stream draining the Bobolice mire amounts to about 46 l/s (Dobrowolski et al. 2010). Unconfined groundwaters supply layer outflows around which hanging spring mires were formed on the valley slopes. In the footslope zone, where there are drainage conditions of intermorainic confined waters supplying efficient ascending springs, cupola spring mires developed.

The groundwaters in the Chociel River valley supplying the spring mires are distinguished by a medium mineralization (297–370 μScm⁻¹) and a neutral reaction (7.1–7.8 pH). Cations of calcium and anions of bicarbonate prevail in the water ionic composition (concentrations of Ca²⁺: 35–60 mgdm⁻³; HCO₃⁻: 98–169 mgdm⁻³ (Osadowski 2010). According to the ecological classification (Succow 1988), these spring mires are eutrophic-calcareous and mesotrophic-calcareous.

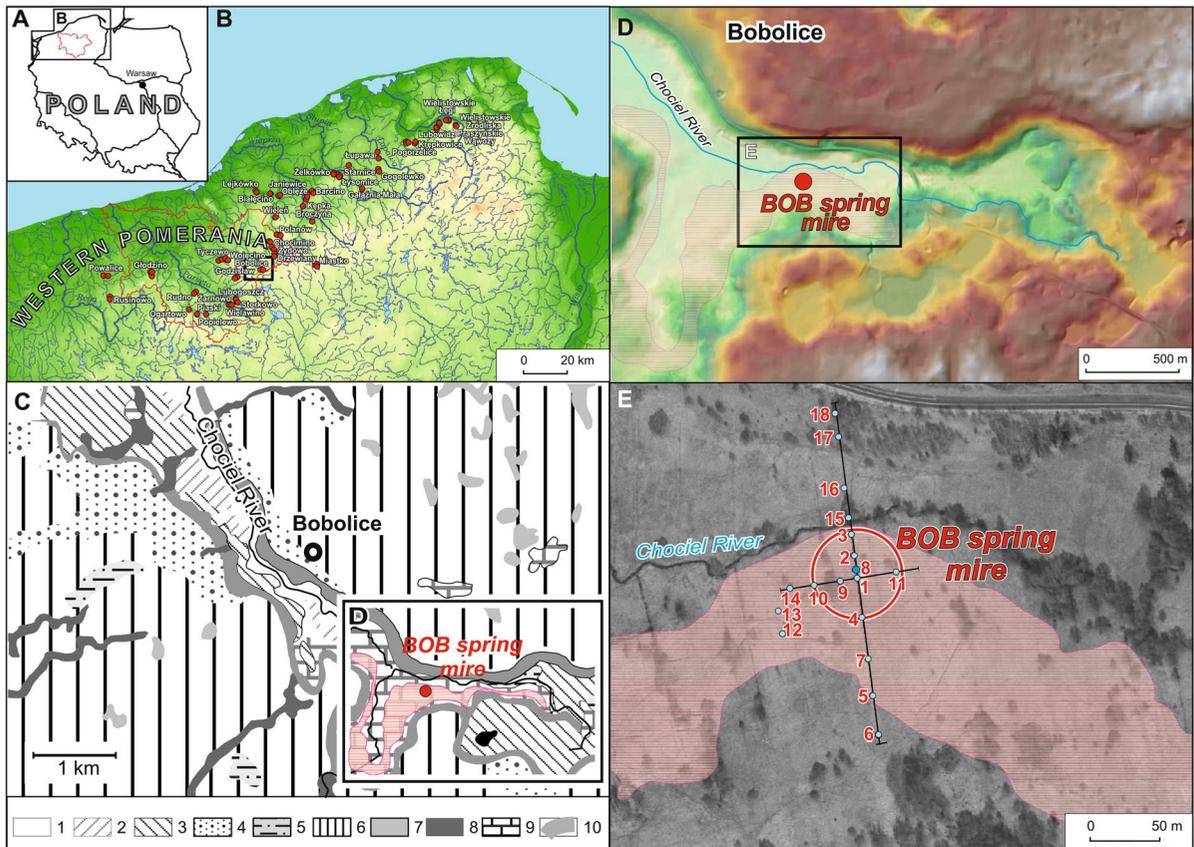


Fig. 1 Study site: in relation to Poland (A); in relation to spring areas in Western Pomerania (B); geological-geomorphological sketch of the upper part of the Chociel River valley (C): 1. River valley floors and floodplains/Alluvia, peats and organic silts, 2. Accumulation river terraces/Fluvial sands, gravels and silts, 3. Cut-and-built fluvio-glacial plains and valleys/Fluvioglacial sands and gravels, 4. Outwash plains/Fluvioglacial sands and gravels, 5. Kame/Kame sands and silts, 6. Undulating morainic upland/morainic gravels, sands and tills, weathered tills, 7.

Melt-out basins without outflow/organic-rich colluvia, colluvia, peat, 8. Erosional-denudational valleys/colluvia, organic-rich colluvia, 9. Peat plains/peat, 10. Slopes/scarps of subglacial tunnel valleys and melt-out tunnels used and modified by rivers, (based on Marszałek and Szymański 2005, modified); relief of the upper part of the Chociel River valley with location of BOB spring mire (grey circle)—studied in detail (D); distribution of boreholes (E). Red area (Fig. 1C–E) marks calcareous tufa deposits in the Chociel River valley. (Color figure online)

Materials and methods

Field work

Phytosociological methods

Real vegetation in the Chociel River valley was surveyed using the phytosociological method according to Braun-Blanquet (Matuszkiewicz 2005). Altogether, 65 floristic inventories were carried out on the peat substrate and what was set together in a shortened synthetic table. For every species a phytosociological constancy according to the five-level Braun-Blanquet's scale and cover ratio according to Tüxen and

Ellenber were taken into account. Species occurring occasionally were not considered in the table. Classification and names of plant communities followed Matuszkiewicz (2005), the moss nomenclature was according to Ochyra et al. (2003) and the vascular plant nomenclature—according to Mirek et al. (2002).

To draw current maps of real vegetation the points of floristic inventories were fitted into calibrated aerial colour photographs (orthophotomap in scale 1:5000), taken by the authors in summer 2010. The analysis of the identified links between vegetation systems combined with features of the photographic images of sites allowed for the preparation of a key used for the interpretation of vegetation units on the remaining

fragments of the valley (Tomaszewska 1988; Stańko et al. 1996). Results of photointerpretation were adjusted during field trips through the visual inspection of real ranges of plant communities. In order to determine the general trends in anthropogenic changes in the natural environment of the Chociel valley, a comparative analysis of historical cartographic materials was carried out, after their previous georeferencing. The following maps were used for this purpose: (1) German geological and soil maps, Geologische Karte von Preussen from 1893, scale 1:25,000 (Bublitz sheet), (2) German topographic maps Mestichblatt from 1936, scale 1:25,000 (Bublitz sheet), and (3) topographic maps from 1986, scale 1:10,000. The ranges of mires, meadows and forests, changes in hydrological networks, and the development of the settlement network and roads were compared on the maps.

Geological survey

We analysed the lithology of the whole peat bed filling the upper part of the Chociel valley near Bobolice. Along the plotted transect, perpendicular to the axis of the valley, geological drillings were performed (within and in the immediate vicinity of a copula spring mire BOB—at a distance of 5–15 m, and every 20–50 m outside the spring mire), and cores with undisturbed structure of deposit were sampled. Drilling works were done using: (1) a hand drill from Eijkelpamp, with an Instorf sampler, 50 cm long, 5 cm in diameter (to explore the peat bed) and (2) an Eijkelpamp percussion drilling set with a closed sampler with a transparent liner—1 m long, 5 cm in diameter (to collect the core for laboratory analysis). In total, 18 drillings were made in the entire study area, including 8 within the copula spring mire coded BOB (Fig. 1D). The core of peat-tufa deposits (BOB-8 core) of 800 cm long for the multiple analyses, representative for the whole spring-fed mire, was sampled at the highest point of its copula (φ 55°56'33" N; λ 16°37'07" E; 113–117 m a.s.l.). Its macroscopic lithofacial analysis, using the non-genetic Troels-Smith formula (Troels-Smith 1955) with modification proposed by Dobrowolski (2011), as well as the results of radiocarbon dating for selected biogenic samples, was presented by Mazurek et al. (2014).

Laboratory analyses

Plant macrofossil analysis

For plant macrofossil analysis the whole sediment core (800 cm) was initially taken. Finally, a 1 m-long segment from the bottom layer was excluded from the analysis, because of the lithology of deposits (fluvial coarse sand and only a few percent of organic matter). The analysed core was divided into 5 cm segments. Altogether, 140 samples of peat and travertine calcareous tufa were collected. For analysis, approximately 50 cm³ of sediment from each sample was flooded with distilled water with the addition of 10% KOH. Next, the suspensions were boiled, then washed out on a 0.2 mm sieve, and sediment was placed in Petri dishes. Vegetative plant remains (roots, epiderm, periderm, rhizoderm, leaves, stems, and wood) were identified under a Leica DM 3000 light microscope with 200×–400 magnification. They were identified with the help of Katz et al. (1977), Hedenäs (2003), Mauquoy and van Geel (2007), and the collection of macroscopic plant remains at the Institute of Biology, University of Białystok. We estimated peat samples for botanical composition, based on a percentage proportion of each taxon tissues in total tissue mass. In the bottom part of the core, as well as in the above-lying calcareous travertine, it was only possible to identify the presence of plant remains. The reason was the small or even trace amount of organic matter. The results of plant macrofossil analysis were presented on a histogram drawn with POLPAL software (Nalepka and Walanus 2003). Recognition of macrofossil zones in the peat layer was mainly based on stratigraphically constrained cluster analysis (CONISS) (Grimm 1987), while for calcareous travertine such delimitation was based on a subjective approach due to the specific plant macrofossil record.

Results

Current state of hydrological conditions and plant cover

In the Chociel valley current real vegetation is an effect of the presence of different mire habitats as well as different forms of agricultural use in the last century. More than 30 types of plant communities

from 6 classes of vegetation were noted: *Montio-Cardaminetea* Br.-Bl. et R.Tx. 1943, *Phragmitetalia* R.Tx. et Prsg 1942, *Scheuchzerio-Caricetea* (Nordh. 1937) R.Tx. 1937, *Molinio-Arrhenatheretea* R.Tx. 1937, *Alnetea glutinosae* Br.Bl. et R.Tx. 1943 and *Quercu-Fagetea* Br.-Bl. et Vlieg. 1937 (Osadowski 2000).

In spring-fed fens semi-natural meadow communities from *Molinio-Arrhenatheretea* R.Tx. 1937 class dominate (Table 1; Figs. 2, 3). Wet habitats are occupied by *Filipendulo-Geranium* W. Koch 1926 with *Filipendula ulmaria* and *Geranium palustre* as dominants. Considerable mire areas are covered by meadows *Molinietum caeruleae* W.Koch 1926. They are the floristically richest plant communities, with 50 plant species. This association is well represented by species of *Molinion caeruleae* W.Koch 1926 alliance, including the rare fern *Ophioglossum vulgatum*. The biggest areas of spring-fed fens are covered by wet meadows from alliance *Calthion palustris* R.Tx. 1936 em. Oberd. 1957. The important role in the secondary peat-forming process is assigned to association *Caricetum caespitosae* (Steffen 1931) Klika et Smarda 1940. It occupies large areas in the studied valley, often forming high clumps, which efficiently prevent the restoration of mowing. High clumps of *Carex caespitosa* became a habitat for the rare arctic-boreal relic *Polemonium coeruleum*. Deeply dehydrated cupolas of spring-fed fens, with mineralized peat are mostly covered by *Urtico-Phragmitetum australis*. This association physiognomically resembles aquatic reed rush. However, it abounds in meadow species from the *Molinio-Arrhenatheretea* class. The transitional phytocoenoses towards *Urtico-Phragmitetum australis* are often represented by nitrophilous communities with *Anthriscus sylvestris* and *Phalaris arundinacea*. Special care and protection should concern naturally valuable *Polygono bistortae-Trollietum europaei* meadows (Hundt 1964) Bal.-Tul. 1981. They are probably constantly supplied by groundwater rich in calcium carbonate. Their characteristic species include numerous rare and endangered ones, including the biggest population of *Trollius europaeus* in Pomerania. The largest area in the valley is occupied by a community with *Carex acutiformis*. Physiognomically it resembles the rush *Caricetum acutiformis* Sauer 1937 from the *Phragmitetea* R.Tx. et Prsg 1942 class, but there are also numerous species of wet meadows and herbs from the *Molinio-*

Arrhenatheretea class. This community, in places intensively supplied by groundwater, forms moss patches with rare relic mosses, like *Helodium blandowii* and *Tomentypnum nitens*.

Plant macrofossils

We identified macrofossils representing 21 plant taxa of various ranks: section, species, genus and family. Plants identified based on macrofossils were grouped according to their morphological forms and taxonomy: trees and shrubs—3 taxa, herbaceous plants—6, *Sphagnum* mosses—3, brown mosses—7, pteridophytes—2. In the Bobolice 8 profile (BOB-8) we distinguished seven local macrofossil zones, giving also their chronological frameworks (Fig. 4).

BOB-8-I zone (700–325 cm). This zone is characterised by a very low frequency of plant macrofossils. In organic-mineral rhythmite (700–665 cm) remains of brown mosses, including *Tomentypnum nitens*, *Meesea triuquetra*, *Aulacomnium palustre* and *Bryum* sp were recognised. In addition—tissues of *Carex* sp., *Equisetum limosum*, *Typha* cf. *latifolia* and sporangia of *Thelypteris palustris*. This macrofossil record indicates the functioning of communities with brown mosses. Their occurrence was connected with the Younger Dryas (11,800–11,500 cal. BP). In peat-tufa rhythmite (665–325 cm) *Carex* sp. radicles were noted regularly. They were accompanied by Bryales remains. Among others identified tissues rhizoderm of *Equisetum limosum*, epiderm of *Phragmites australis* and *Typha* cf. *latifolia*, as well as roots of *Cladium mariscus* were described. Sporangia of *Thelypteris palustris* also occurred. Plant macrofossil record of BOB-8-I zone indicates that during deposition of calcareous tufa vegetation of spring-fed fen was represented by sedge communities with brown mosses and rushes taxa. This phase was interrupted in the Atlantic period (7900 cal. BP).

BOB-8-II zone (325–225 cm). This zone is connected with the lowest level of peat. Identified macrofossils mainly included roots of sedges (maximum 65% per sample), up to 10% admixture of roots of *Cladium mariscus*, trace amounts of *Typha* cf. *latifolia* tissues and fragments of *Sphagnum* sp. and Bryales leaves. This macrofossil zone concerns the Atlantic age sediment (7900 cal. BP–6000 cal. BP).

BOB-8-III zone (225–150 cm). The main component of the deposit were roots of *Carex* sp., which form

Table 1 Plant communities of BOB spring-fed fen in the Chociel River valley

Syntaxonomic unit	1	2	3	4	5	6	7	8
Number of records in the table	5	5	15	10	10	10	5	5
Number of species in the table	33	50	37	34	22	27	25	15
Average number of species in the record	27	33	29	26	16	22	19	12
Min. number of species in the record	23	18	20	18	9	9	15	8
Max. number of species in the record	33	50	37	34	22	27	25	15
Minimum cover c [%]	90	90	90	80	80	80	60	90
Maximum cover c [%]	100	100	100	100	100	100	100	100
Minimum cover d [%]	5	0	5	1	0	0	0	0
Maximum cover d [%]	10	20	30	5	10	30	5	5
Record area [m ²]	25–50	25–50	25–25	25–50	25–50	16–50	25–50	16–25
Ch. et D. Ass.								
<i>Filipendula ulmaria</i>	V-5600	IV-390	IV-443	IV-215	IV-135	IV-440	IV-220	II-700
<i>Geranium palustre</i>	V-1062	III-210	IV-823	IV-515	IV-465	–	III-30	–
<i>Molinia caerulea</i>	–	V-3750	III-1130	III-200	–	–	–	–
<i>Trollius europaeus</i>	–	–	V-4017	–	–	–	–	–
<i>Polygonum bistorta</i>	IV-388	IV-320	V-842	II-220	III-85	IV-170	IV-40	I-10
<i>Carex caespitosa</i>	II-438	III-1050	II-276	V-6000	III-115	II-155	II-110	III-210
<i>Phragmites australis</i>	–	IV-400	IV-463	III-710	V-6800	II-185	–	II-360
<i>Urtica dioica</i>	III-450	II-20	–	III-245	V-2525	II-20	IV-470	IV-720
<i>Carex acutiformis</i>	IV-912	V-1250	IV-753	III-410	IV-855	V-7000	III-210	I-10
<i>Anthriscus sylvestris</i>	II-25	–	–	II-280	II-230	–	V-5250	I-10
<i>Phalaris arundinacea</i>	–	–	–	–	–	–	–	V-7250
Ch. All. <i>Filipendulion ulmariae</i>								
<i>Lythrum salicaria</i>	II-110	II-110	–	II-15	–	III-25	–	II-20
<i>Lysimachia vulgaris</i>	–	I-10	–	II-60	III-25	IV-125	–	III-30
<i>Epilobium hirsutum</i>	–	–	–	II-15	III-115	II-20	–	II-20
<i>Epilobium palustre</i>	II-12	–	–	–	–	II-65	–	–
<i>Stachys palustris</i>	III-138	–	–	–	–	–	–	–
Ch. et D. All. <i>Molinion caeruleae</i>								
<i>Selinum carvifolia</i>	–	V-230	I-20	–	–	–	–	–
<i>Briza media</i>	–	III-110	I-20	–	–	–	–	–
<i>Succisa pratensis</i>	–	V-120	–	–	–	–	–	–
<i>Galium boreale</i>	–	II-47	–	–	–	–	–	–
<i>Ophioglossum vulgatum</i>	–	I-10	–	–	–	–	–	–
Ch. et D. All. <i>Calthion palustris</i>								
<i>Cirsium oleraceum</i>	III-250	IV-220	IV-183	IV-340	II-65	II-65	III-120	I-10
<i>Geum rivale</i>	III-25	IV-230	III-30	IV-265	II-65	IV-80	III-30	–
<i>Scirpus sylvaticus</i>	IV-375	II-20	III-170	–	–	II-155	III-210	II-110
<i>Crepis paludosa</i>	III-25	III-460	IV-100	–	II-15	II-60	–	II-20
<i>Juncus effusus</i>	II-25	IV-460	III-117	–	–	–	–	–
<i>Myosotis palustris</i>	II-12	–	–	–	I-10	III-25	–	–
<i>Dactylorhiza majalis</i>	II-12	II-20	II-17	–	–	–	–	–
<i>Caltha palustris</i>	III-25	–	–	–	I-5	–	–	–
Ch. O. <i>Molinietalia caeruleae</i>								
<i>Equisetum palustre</i>	V-1125	II-230	III-267	II-385	II-190	IV-260	–	–

Table 1 continued

Syntaxonomic unit	1	2	3	4	5	6	7	8
<i>Galium uliginosum</i>	IV-150	III-120	III-210	IV-215	–	IV-175	–	–
<i>Cirsium palustre</i>	IV-38	III-30	II-13	–	–	IV-85	–	–
<i>Deschampsia caespitosa</i>	III-250	IV-810	III-573	II-275	–	–	–	–
<i>Lychnis flos-cuculi</i>	–	III-30	III-60	–	–	II-60	–	–
<i>Lotus uliginosus</i>	–	II-200	–	–	III-25	II-235	–	–
<i>Climacium dendroides</i> d	–	–	III-303	–	–	II-275	–	–
<i>Angelica sylvestris</i>	–	–	II-46	III-115	–	–	–	–
<i>Achillea ptarmica</i>	–	IV-130	II-20	–	–	–	–	–
Ch. Cl. Molinio. Arrhenatheretea								
<i>Lathyrus pratensis</i>	IV-275	IV-40	IV-153	III-210	II-65	II-185	III-30	–
<i>Festuca rubra</i>	III-250	V-1500	IV-920	–	I-100	–	–	–
<i>Poa trivialis</i>	–	–	II-250	III-500	I-180	II-275	–	III-800
<i>Poa pratensis</i>	III-450	II-450	II-467	–	–	–	–	–
<i>Avenula pubescens</i>	II-125	II-200	III-180	III-115	–	–	–	–
<i>Vicia cracca</i>	III-25	–	II-17	IV-125	–	–	–	I-10
<i>Holcus lanatus</i>	IV-262	IV-400	III-300	III-675	–	–	III-90	–
<i>Alopecurus pratensis</i>	III-128	III-120	–	–	–	–	III-300	–
<i>Phleum pratense</i>	II-125	–	–	–	–	–	II-450	–
<i>Pimpinella major</i>	–	–	IV-127	II-110	–	–	–	–
<i>Festuca pratensis</i>	–	III-210	–	II-150	–	–	–	–
<i>Dactylis glomerata</i>	–	–	II-13	II-105	–	–	–	–
<i>Ranunculus acris</i>	–	–	II-20	–	–	–	–	I-10
Comp.								
<i>Calligonella cuspidate</i> d	IV-347	IV-650	IV-753	–	–	III-750	–	II-110
<i>Brachythecium rutabulum</i> d	II-125	–	III-520	II-155	II-280	–	II-110	II-20
<i>Galium aparine</i>	III-23	–	–	II-190	V-760	–	V-1500	III-210
<i>Plagiommium elatum</i> d	IV-262	III-550	V-1017	–	–	III-850	–	–
<i>Galeopsis tetrahit</i>	–	II-20	–	–	–	–	IV-470	III-210
<i>Veronica chamaedrys</i>	–	II-20	IV-93	II-65	–	–	–	–
<i>Cirsium arvense</i>	–	–	–	II-20	–	–	IV-30	II-20
<i>Valeriana dioica</i>	–	II-110	II-47	–	–	III-160	–	–
<i>Rhynchospora squarrosa</i> d	–	II-110	III-147	–	–	–	–	–
<i>Galeopsis speciosa</i>	–	–	–	III-120	II-110	–	–	–
<i>Deschampsia caespitosa</i>	–	–	–	–	–	–	IV-560	II-20
<i>Salix cinerea</i>	–	–	–	–	II-60	II-65	–	–
<i>Carex paniculata</i>	III-250	–	–	–	–	III-410	–	–
<i>Equisetum fluviatile</i>	III-138	III-30	–	–	–	III-70	–	–
<i>Plagiommium undulatum</i> d	–	II-110	–	–	–	–	–	–
<i>Potentilla erecta</i>	–	II-20	–	–	–	–	–	–
<i>Carex rostrata</i>	–	–	–	–	–	III-70	–	–
<i>Anthoxanthum odoratum</i>	–	–	II-140	–	–	–	–	–
<i>Peucedanum oreoselinum</i>	–	–	–	II-230	–	–	–	–
<i>Polemonium coeruleum</i>	–	–	–	II-60	–	–	–	–
<i>Cerastium fontanum</i>	–	II-20	–	–	–	–	–	–
<i>Cerastium arvense</i>	–	–	II-47	–	–	–	–	–
<i>Glechoma hederacea</i>	–	–	–	–	–	–	II-450	–
<i>Stellaria graminea</i>	–	–	–	II-20	–	–	–	–

up to 65% of the sample. Deciduous wood was also present (max. 80%), as well as admixture of periderm from *Salix* sp. and *Betula* sp., remains of *Equisetum*

limosum and *Typha* cf. *latifolia*. Peat mosses, including those representing the *Palustria* section, and brown mosses were noted in peat mass. This zone

Table 1 continued

Syntaxonomic unit	1	2	3	4	5	6	7	8
<i>Helodium blandowii</i> d	–	–	–	–	–	I-20	–	–
<i>Tomentypnum nitens</i> d	–	–	–	–	–	I-10	–	–
<i>Aulacomnium palustre</i> d	–	–	–	–	–	I-10	–	–

Cl. Molinio-Arrhenatheretea R.Tx. 1937, O. *Molinietalia caeruleae* W.Koch 1926, All. *Filipendulion ulmariae* Segal 1966

1. Ass. *Filipendulo-Geranietum* W.Koch 1926. All. *Molinion caeruleae* W.Koch 1926
2. Ass. *Molinietum caeruleae* W.Koch 1926. All. *Calthion palustris* R.Tx. 1936 em. Oberd. 1957
3. Ass. *Polygono bistortae-Trollietum europaei* (Hundt 1964) Bal.-Tul. 1981
4. Ass. *Caricetum cespitosae* (Steffen 1931) Klika et Smarda 1940
5. Ass. *Urtico-Phragmitetum* Succ. 1970
6. Comm. *Carex acutiformis*
7. Comm. *Anthriscus sylvestris*
8. Comm. *Phalaris arundinacea*

refers mainly the Subboreal age sediments (6000 cal. BP–4400 cal. BP).

BOB-8-IV zone (150–90 cm). In contrast to the previous level, a lack of wood and periderm was noted. The share of sedge roots reached 80% of the macrofossils in the sample, and *Phragmites australis*—not more than 10%. The presence of brown mosses (max. 10%) was recorded, including *Drepanocladus* sp., *Philonotis* cf. *fontana*. Remains of *Sphagnum* reached even 20% per sample. The plant record concerns the Subboreal period (4400 cal. BP–3200 cal. BP).

BOB-8-V zone (90–65 cm). Identified macrofossils included radicles of *Carex* sp. (max. 75% per sample), and the share of Bryales and *Sphagnum* remains was up to 20% per sample. The upper limit of this zone indicates ca. the Subboral/Subatlantic turn (2600 cal. BP).

BOB-8-VI zone (65–10 cm). Sedges were still dominant in peat (max. 75%), *Sphagnum* reached up to 40% of the sample, while Bryales remains were sporadic and only in trace amounts. This zone concern the Subatlantic period (2600 cal. BP–400 cal. BP).

Macrofossil zones BOB-8-II—BOB-8-VI are the record of sedge vegetation. However, admixture of rushes, brown moss communities and birch-alder-willow thickets is also reflected.

BOB-8-VII zone (10–0 cm). The last macrofossil zone, connected with the youngest phase of mire development (younger than 400 cal. BP), was characterised by a significant decrease in the share of

Carex sp. radicles (to 5%). Among identified macrofossils *Sphagnum* sp. (max. share 55% in the sample), and *Sphagnum teres* (max. 20%) were represented. This zone is a reflection of peat moss succession on the mire.

Discussion

Vegetation history of Bobolice (BOB) spring-fed fen

Results of multiple analyses allowed for (1) the reconstruction of major evolutionary phases in the BOB spring-fed fen in the Chociel River valley near Bobolice, (2) identification of the main directions of ecological succession, corresponding with the chronostratigraphy of the Late Glacial and the Holocene (see Mangerud et al. 1974).

Phase 1: ca. 12650 cal. year BP

The biogenic succession started between the late Allerød and early Younger Dryas, which is documented by radiocarbon dating (Mazurek et al. 2014), and results of pollen analyses (Pidek et al. 2012). Relative amelioration of the climate at the end of the Late Glacial promoted the melting of dead ice blocks and the formation of shallow water bodies in meltout basins in the spring section of the Chociel River

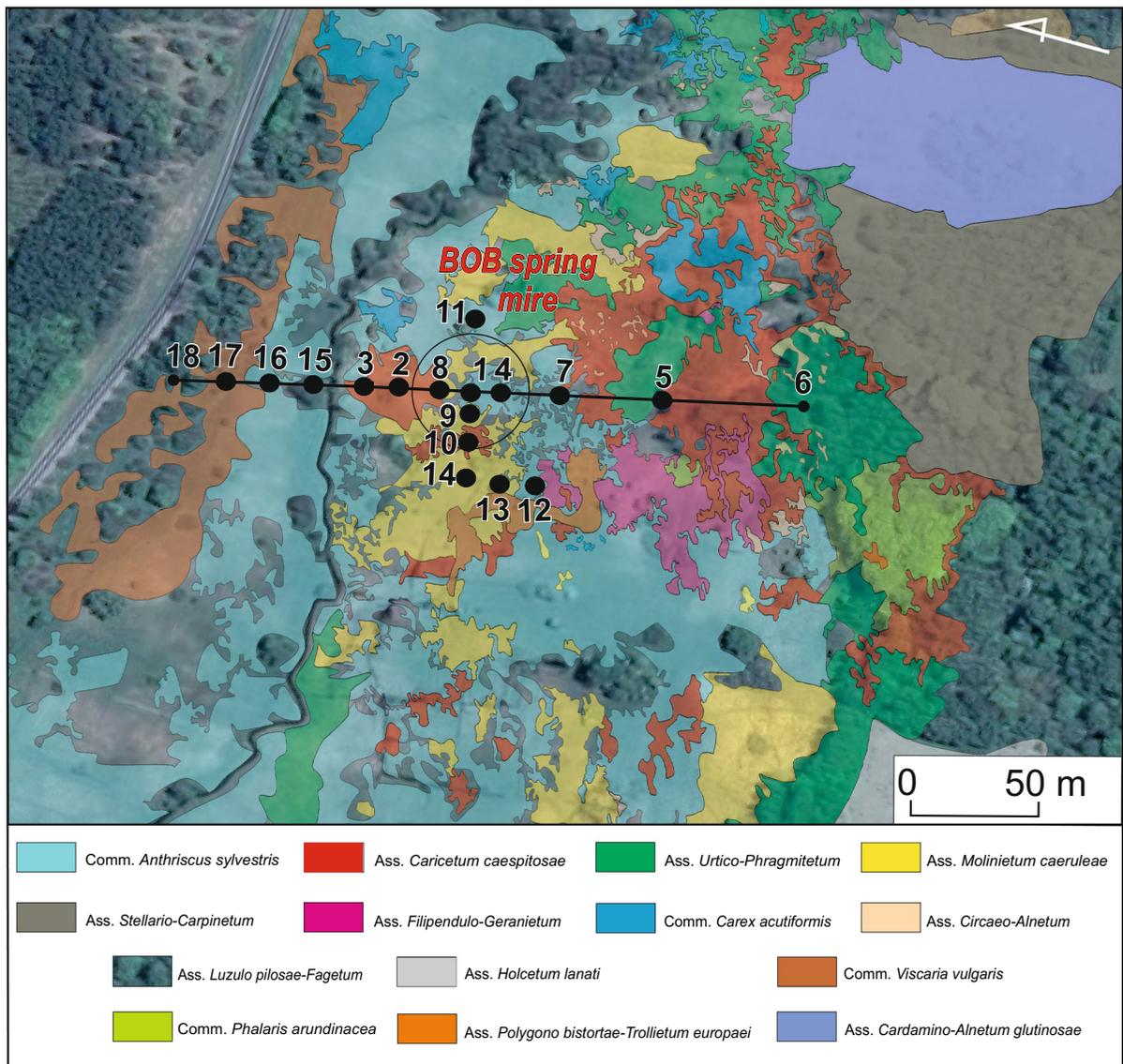


Fig. 2 Map of real vegetation on spring-fed fens in the upper Chociel River valley. (Color figure online)

valley. The sediments of these meltout basins contain only a few percent of carbonates, while the content of lithophilic elements: magnesium, potassium and zinc, is high, documenting the dominance of mechanical denudation in the Chociel River catchment area. Saturated fluvio-glacial sand substrates were covered by hygrophilic communities, probably mainly sedges; as a consequence, a thin layer of strongly decomposed peat was formed, constituting the first stage of organic sedimentation. The presence of Late Glacial basal peat on mineral sediments filling subglacial tunnels and

melt outs is common throughout the Polish Lowlands (Nowaczyk 2008; Wojciechowski 2000; Błaszczewicz 2005).

Phase 2: 12650–11500 cal. year BP

Initially, with the deterioration of the climate in the Younger Dryas, biogenic sedimentation was replaced by mineral river-periglacial sedimentation. It is documented by the presence of fine sands, heavily contaminated with calcium carbonate (Marszałek

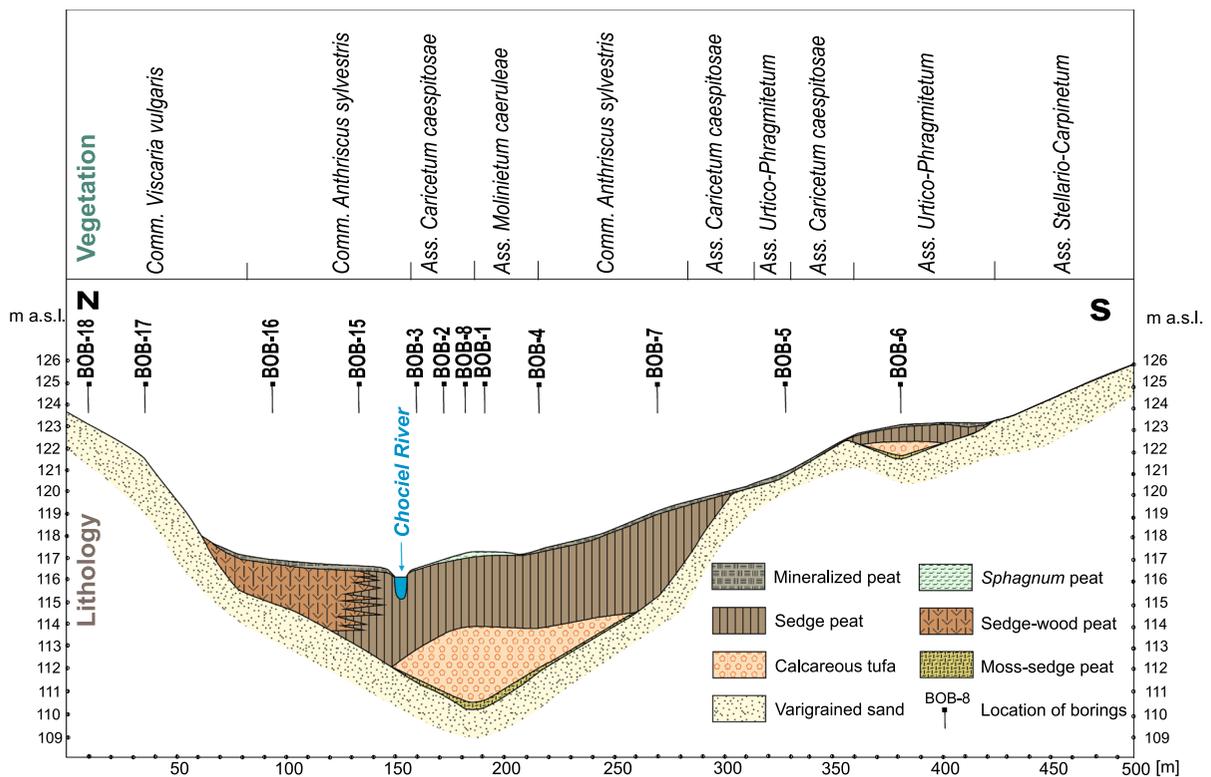


Fig. 3 Geological profile of mires in the Chociel River valley (transect BOB—location as in Fig. 1E). (Color figure online)

and Szymański 2005). The carbonates initially underwent redeposition within near-surface deposits in the permafrost conditions. Surface and/or sub-surface runoff water in the active layer of permafrost, enriched with calcium carbonate of cryogenic origin, fed the shaping Chociel River valley. A warm episode at the end of Younger Dryas contributed to the gradual change in the conditions of groundwater circulation (= ascending groundwater supply), resulting in the development of soligeneous habitats with mossy vegetation and elements of rushes, documented by the presence of moss-sedge peat in the deposition bed. This is evidenced by the presence of macrofossils of *Typha cf. latifolia*, *Equisetum limosum* and brown mosses, including *Tomentypnum nitens*, *Meesea triquetra* and *Aulacomnium palustre* (macrofossil level BOB-8-I; depth 700–665 cm; Fig. 4). The presence of the first two listed species indicates the supply of groundwater rich in calcium carbonate (Ochyra 1992), while *Aulacomnium palustre* is an element of minerotrophic communities, partly associated with rainwater (Matuszkiewicz 2007).

Phase 3: 11500–7900 cal. year BP

This is the major phase of the development of the spring-fed fen sensu stricto, associated with the final degradation of permafrost and complete unblocking of the ascending groundwater supply. In the lithological record it is documented by the thick layer of peat-tufa rhythmite (sensu Dobrowolski 2011), reflecting changes in climate humidity and temperature. Groundwaters, leaching calcium-rich postglacial sediments enriched in calcium cations and bicarbonate anions, and efficient accumulation of calcium carbonates followed around the groundwater discharge zone. Oxidizing conditions and alkaline reaction of water favoured the accumulation of chemical denudation products, resulting in high concentrations of Ca, Na, Mn and Fe in deposits of this phase, while the concentrations of lithophilous elements (Mg and especially K) decreased (Mazurek et al. 2014). Intensive ascending groundwater supply contributed to the development of various sedge communities, also with admixture of brown mosses and *Cladium mariscus*

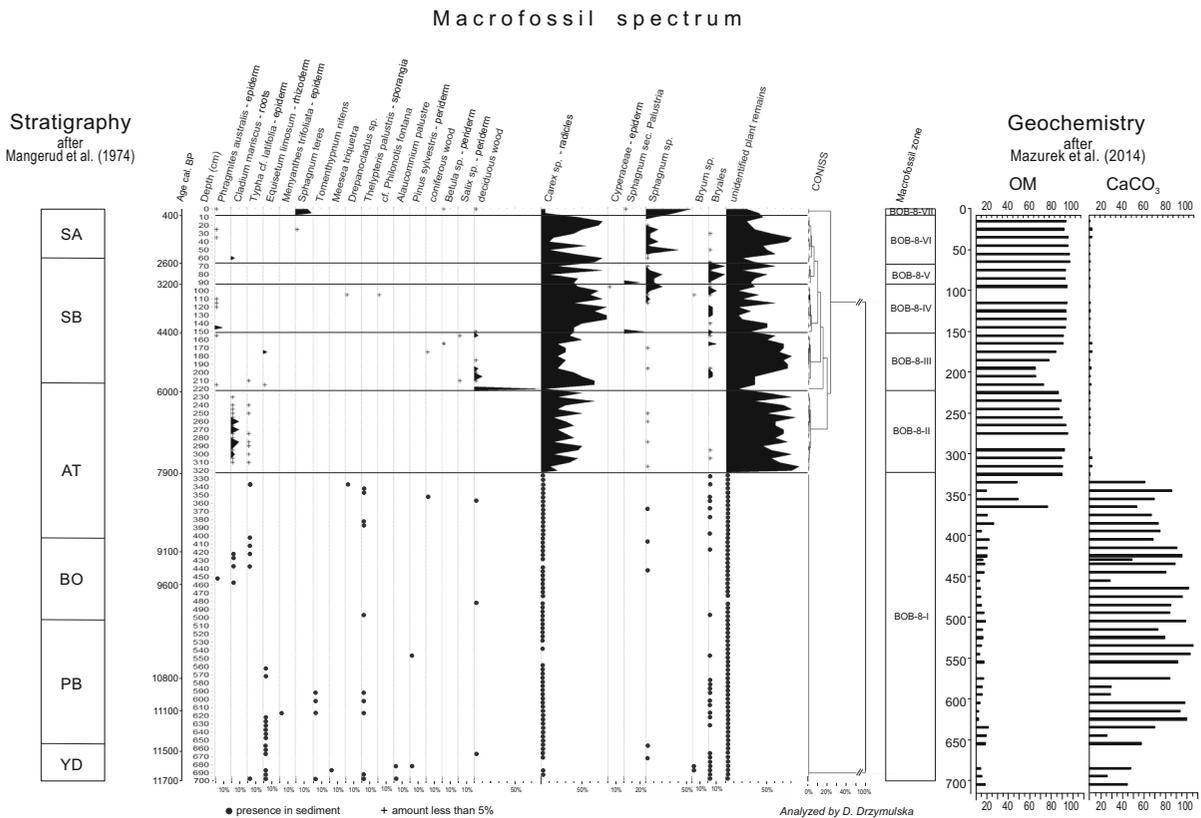


Fig. 4 Diagram of vegetative plant macrofossils for BOB-8 profile

(level BOB-8-I; depth 665–325 cm; Fig. 4) on the spring-fed fen.

Phase 4: 7900–6000 cal. year BP

It corresponds with the discontinuation of the artesian groundwater supply, and as a consequence inhibited the deposition of carbonates and development of helocrene on the top of the spring mire copula. In the lithological record it is documented by the insertion of sedge peat with *Cladium mariscus* (macrofossil level BOB-8-II; Fig. 4). At the same time the concentrations of Ca, Mn and Cu described as the products of chemical denudation, decreased, and under the created redox conditions iron reached the highest concentrations (Mazurek et al. 2014).

Phase 5: 6000–4400 cal. year BP

In this phase, sedge communities were colonized by shrubs, as evidenced by the presence of macrofossils

representing deciduous trees/shrubs, including *Salix* sp. and *Alnus* sp. (macrofossil level BOB-8-III; Fig. 4). This could be due to the domination of drier conditions in that period (relatively long dry phases separated by short humid episodes) and the associated reduction in the level of groundwater of Northern Poland, recorded at the end of the Atlantic and in the early Subboreal periods (Ralska-Jasiewiczowa and Starkel 1988). Total change in environmental conditions is reflected in the geochemical features of the sediments. The supply and deposition of products of chemical weathering in this period were strongly limited (low concentrations of Ca, Fe and Mn), with a slight increase in the concentrations of lithophilous elements: Mg and K. The mire was probably gradually fed by rainwater, which modified the supply of dissolved substances to sediments (increase in Na concentration, which is the dominant cation in rainwater in the studied area), and acidic precipitation could have affected the leaching of deposited

components and their discharge to surface waters, which also changed the habitat conditions.

Phase 6: 4400 cal. year BP—Present

In the first half of the Subboreal period the dominance of communities formed by sedges, peat mosses and brown mosses began (macrofossil levels BOB-8-IV, BOB-8-V, BOB-8-VI and BOB-8-VII; Fig. 4). The creation of this type of plant community was probably related to the dominant role of low-mineralized, more acidic rainwater in the supply of the habitat.

The biogenic sediments with over 50% content of OM, a minimum content of carbonates (2–1%) (Fig. 4) and the low concentration of Ca indicates that the supply and/or precipitation of chemical denudation products to the spring-fed fen were reduced. The more than 3-metre-thick series of the peat-tufa rhythmite could limit the alimentation of this sedimentary basin by groundwater as a result of the substratum becoming sealed and a decline in vertical hydraulic conductivity and the volume of groundwater outflows (Mazurek et al. 2014). Under such conditions, rainwater is an essential component of mire supply.

Natural changes in ecological succession were probably accelerated by the activity of humans, who at that time began the modification of the water regime in the Chociel River valley (Latałowa 1982). Treatments aimed at draining spring mires in the valley clearly intensified 250–300 years ago. As a result, peat moss-sedge peats have mineralized. From that time, human activity intensified in the Chociel River valley, and it was used for agricultural purposes as meadows and pastures.

Human impact on the contemporary plant cover

Historical records documenting the human presence in the Chociel River Valley come from the 8–12th centuries (Malinowski and Malinowski 1990; Wołejko 1996). Several stages of significant transformations in the valley can be identified based on archival maps and landscape analyses (Fig. 5).

Before 1893 the human impact on mires in the valley was relatively small. Watercourses run in their natural beds, and drainage ditches occurred only on small areas of peatlands.

In 1936 the area surrounding the valley was densely populated and intensively used for agriculture. Mires were significantly drained, and transport infrastructure was gradually built (roads, railway line, bridges). In a large area in the bottom of the valley peat was extracted for fuel.

Post-war economic transformations in 1945–1960 caused a decline in local agriculture. In the 1970s the majority of meadows were taken over by large farms, mainly operating on cattle breeding. The process of establishing new meadows and pastures was associated with the removal of thickets and large scale drainage of spring mires in the Chociel valley (in 1987). A significant area of mires was plowed, fertilized and sown with grass mixtures, composed mainly of *Alopecurus pratensis*, *Phleum pratense* and *Lolium perenne*. The top layer of peat has become strongly mineralized.

In the late 1980s, after the economic crisis in Poland, agricultural use was abandoned on the majority of spring-fed fens. Rapid succession of vegetation began on abandoned farmland, starting from meadow communities, through sedges and willow thickets, ending with spring alder woods. This lasted until 2004. After Poland's accession to the EU and the introduction of direct payments, significant areas of peatlands were restored for agricultural use. Restored mowing (and occasionally grazing) on peatlands inhibited the growth of shrubs and trees. Due to the unique natural values, significant areas of mires were included in the European Ecological Network Natura 2000.

Wetland protection and management

Palaeoecological studies conducted on the spring-fed fen in the Chociel River valley provided the necessary knowledge about the history of these ecosystems. Reconstruction of vegetation succession and analysis of hydrogeological and climatic conditions allowed to recognize factors driving their development and preservation in the long time perspective. Look at the past of the studied spring mire seems to be essential for proper protection management of their valuable vegetation cover. Because such actions should depend on the origin of fens, and they will be different for those originating in limnocene conditions (paralimnic environment) rather than in crenic conditions (spring environment), or for mires which were formed in helocrenic conditions (paludic environment).

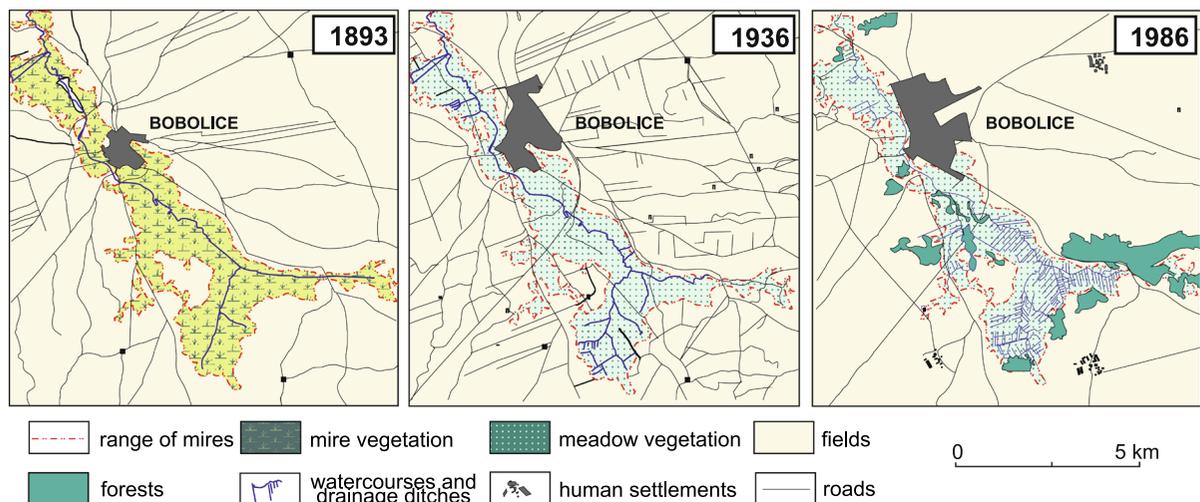


Fig. 5 Changes in the use of mires in the Chociel River valley near Bobolice in 1893–1986: 1—range of mires, 2—mire vegetation, 3—meadow vegetation, 4—fields, 5—forests, 6—

watercourses and drainage ditches, 7—human settlements, 8—road network. (Color figure online)

Mires in the Chociel River valley, in the Bobolice area, are protected by law as a part of the European Ecological Network Natura 2000. They are included in the site PLH320022 “Dolina Radwi, Chocieli i Chotli” (Bobolice). In 2017 some spring-fed fens were turned into a nature reserve, “Łąki Bobolickie”. The surface area of this new reserve is 129 ha. It covers one of the largest well-known concentrations of meadows in Western Pomerania with *Trollius europaeus*. In spite of petitions submitted in consultations with the public, the new reserve does not include the fragment of the valley most valuable for its natural features and the presence of spring mire, which has long been a candidate for the “Źródłiskowe Trawertyny” nature reserve (Osadowski 1999a, b). Despite legal protection, no active conservation measures have been carried out necessary for the preservation of floristically valuable meadow communities formed by *Trollius europaeus*, *Polemonium caeruleum*, *Platanthera chlorantha*, *Epipactis palustris*, *Dactylorhiza maculata*, *D. fuchsii*, *Listera ovata* and the relic moss species *Helodium blandowii*, *Tomentypnum nitens*, *Paludella squarrosa*.

In the Chociel valley cupola spring-fed fens occurred in conditions of intensive ascending groundwater supply (spring environment). These mires were transformed by humans to varying degrees. Mainly they were drained and changed into agricultural grasslands. In effect, very diverse vegetation cover,

often not referring to the phytocoenoses of spring-fed fens at present, appears but recognizable in palaeoecological studies. For the most naturally valuable areas the aim and object of protection, as well as the way to achieve it, have to be defined. The restoration of mowing and removal of shrubs and trees appearing in cupolas of spring-fed fens seems crucial. Regular mowing in the valley could be a big challenge. Fens are strongly hydrated, and additionally they include many places covered by high clumps of *Carex caespitosa*, which efficiently prevents the restoration of mechanical mowing. Therefore, the only effective action is, in our opinion, manual mowing and shrub cutting, as well as the removal of biomass from mire in order to preserve its valuable vegetation.

In the case of extremely degraded spring-fed fens in the Chociel River valley more advanced renaturalisation measures, including (in addition to raising the groundwater level) gradual removal of the top layer of peat earth and the reintroduction of mire species (see Grootjans et al. 2015), will be necessary. Paradoxically, eroding spring-fed fens and exposed layers of calcareous tufa can become a valuable habitat with communities formed by *Cratoneurion commutati* (7220) (Osadowski 2010).

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