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GEOLOGY AND DEVELOPMENTAL PATHWAYS OF SPHAGNUM PEATLAND-LAKE ECOSYSTEMS IN EASTERN POMERANIA

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Abstract

We investigated sediments of three *Sphagnum* peatland-lake ecosystems located in Tuchola forest, both in moraine (Małe Leniwe near Rekowo) and outwash plain (Dury and Rybie Oko) landscape. Geological cross-sections were studied for each basin. Characteristic feature of these ecosystems is the presence of floating mats encroaching the lakes and deposition of highly hydrated sediments below the floating mat. Principal conditions favouring the development of peatland-lake ecosystems are (1) location of the lake in a sandy, non-calcareous catchment overgrown by coniferous forest, (2) steepness of the lake basin, what prevents emerged macrophytes succession and (3) the depth of the basin significantly exceeding 10 m to avoid complete infilling of the lake basin. The developmental pathway in the Dury I basin indicates a shift in lake environment from neutral to acid one. After initial development of *Charophytes*, *Potamogeton* and *Najas* expanded, which later on, were succeeded by *Sphagnum* due to acidification of the lake water. Initial stages of the development of the lakes were determined mainly by allogenic factors, whereas in later stages autogenic factors (development of floating mat and peat acidifying the lake water) played fundamental role.

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Key words: peatland-lake ecosystem, floating mat, peat, lake deposit, autogenic and allogenic factors, lake morphometry

INTRODUCTION

Sphagnum peatland-lake ecosystems are rare but valuable elements of young glacial landscape, occupying a small area, usually 1–5 ha (Tobolski 2003). They develop as a result of growth of floating mat. Vegetation forming floating mat belongs to surface-floating plants (not rooted in the bottom) commonly found also in transitional and raised bog assemblages. Morphology of peatland-lake ecosystems was presented by Banaś (2010).

Sphagnum peatland-lake ecosystems constitute a transitional stage occurring before the stage of a lake entirely overgrown by peatland, specified in literature as kettle-hole peatland (*e.g.* Ilnicki 2002, Tobolski 2003, Lamentowicz *et al.* 2007, Timmermann 1999, Timmermann, Succow 2001). An example of the initial stage of development of a peatland-lake ecosystem is Lake Małe Łowne (Kowalewski *et al.* 2009, Milecka, Tobolski 2009), still not determined as a peatland-lake ecosystem. Geological structure of peatland-lake ecosystems, particularly formations in the floating mat zone, is still studied to little extent (*e.g.* Kratz, De Witt 1986, Winkler 1988, Kowalewski, Milecka 2003, Kordowski, Słowiński 2010). It should be emphasised that the majority of geological studies on this type of lakes have been focused on peatlands and their genesis (*e.g.* Kloss 1993), whereas they usually avoided analyses of limnic sediments under peats.

The process of overgrowing in *Sphagnum* peatland-lake ecosystems proceeds in two manners: by filling the basin with limnic sediments (sedimentation), and by growth of floating mat resulting in peat development (sedentation). In the second case, apart from gyttjas and peats, also formations of sedimentary origin develop, including both limnic and peat components falling from the floating mat. This causes significant problems in their description (Kowalewski 2009). The present paper describes the sedimentation patterns typical of a lake basin covered with floating mat, based on analysis of three objects: Dury I, Rybie Oko and Małe Leniwe. Hydroseral development of Lake Dury I was reconstructed based on detailed examination of sediment components.

STUDY AREA

The study was carried out on Dury (the Wda River outwash plain) and Rybie Oko (the Brda River outwash plain) peatlands, and in the moraine area, on Małe Leniwe peatland in the vicinity of Rekowo (Bytowskie Lakeland). Location of these sites is shown in Figure 1.

Dury I

Dury I peatland (53°38’22’’N, 18°21’12’’ E) is located approximately 4.5 km north of the Osie village, on the eastern side of the road leading to Skórcz. The studied site is the north-westernmost basin of the five constituting the “Dury”

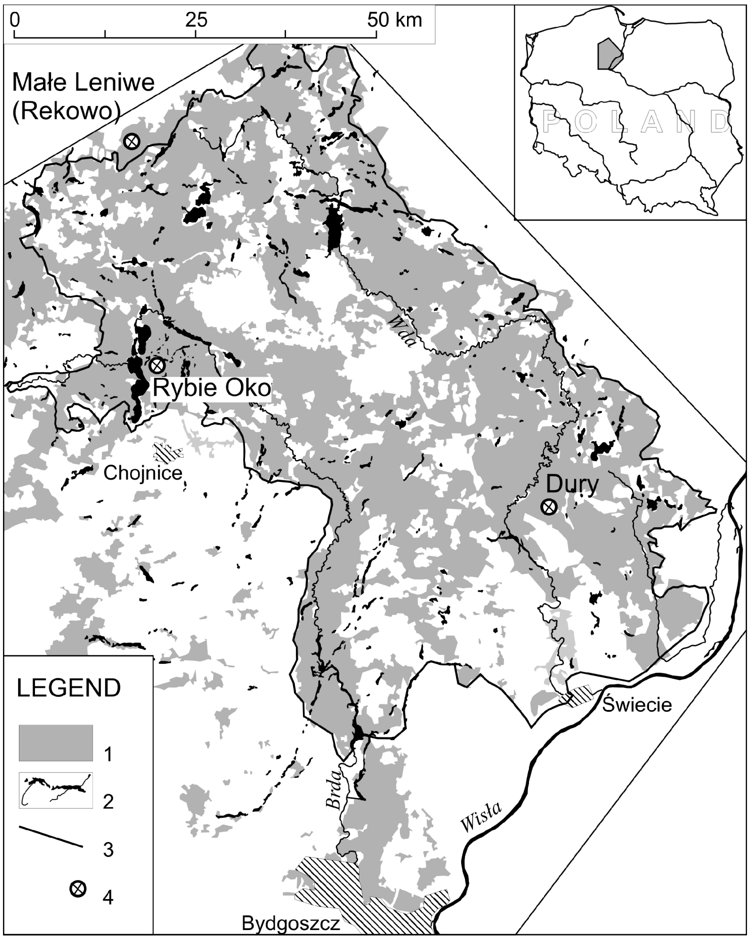


Fig. 1. Location of investigated peatlands. Explanation: *1* – forests, *2* – lakes and rivers, *3* – border of Tuchola Pinewood according to Kowalewski (2002), *4* – investigated sites.

reserve, and it occupies the area of 3.5 ha (including the lake). The altitude of the lake, located in the northern part of the peatland, is 91.5 m a.s.l. The sandy-gravel outwash plain surrounding the peatland reaches 95–96 m a.s.l., and slopes along the Wda River valley and the eastern trail in the vicinity of Lipinki down to 90 m a.s.l. in the area of the Vistula River valley (Makowska 1972, 1975). The outwash plain begins at the forefield of the Pomeranian Phase moraines at the altitude of approximately 150 m a.s.l. in the region of Konarzyny and Stara Kiszewa, and slopes down southwards, interspersed with numerous arid closed-drainage basins and isolated dune hills. Only deeper depressions, such as Dury peatland, or valleys in places of former channels, such as Sobińska Struga, were subject to paludification and peat forming processes.

Dury peatland is fed by waters of an underground water body with a slightly inclined surface and low discharge. The water body is fed mainly by precipitation waters. Peatlands develop in places where the first unconfined aquifer is intersected with the ground surface, irrespective of the depth of the aquitard. Dury peatland is, therefore, a peatland of a topogenic alimentation type (compare Żurek 1990a, b).

Rybie Oko

Rybie Oko peatland (53°48’50’’N, 17°32’18’’E) is located approximately 300 m south of the southern shore of Lake Płęsno, and 600 m east of Lake Skrzynka (Tuchola Forest National Park). Its shape of an isosceles triangle with an oval lake in the middle was the reason for giving it the name (Fish Eye). The western and eastern fringes are mainly occupied by assemblages of *Eriophorum vaginatum* L., currently significantly dried. Closer to the centre of the peatland, marshy coniferous forest occurs, extending to the floating mat. The peatland, located in a closed-drainage basin (129.5 m a.s.l.), is surrounded by outwash plains elevated by 8–10 m. The lower Brda River outwash plain level (135–138 m a.s.l.) is interspersed with numerous linear dunes located approximately 5–10 m higher. According to Nowaczyk (2006), to the south of the peatland, the first outwash plain level occurs (140–141 m a.s.l.), occupied by dunes. On the hydroisohips map (Nowicka 2006), waters of Rybie Oko peatland are perched by 5–6 m in relation to the first continuous aquifer. According to hydrologists, however (Nowicka, Lenartowicz 2004), perched waters are in hydraulic contact with the continuous aquifer. Therefore, in spite of its significantly elevated surface, the peatland can be fed by underground waters inflowing from the side.

Małe Leniwe

Małe Leniwe peatland (54°05’04’’N, 17°28’21’’E) is located at a distance of 2 km east of the Rekowo village, and

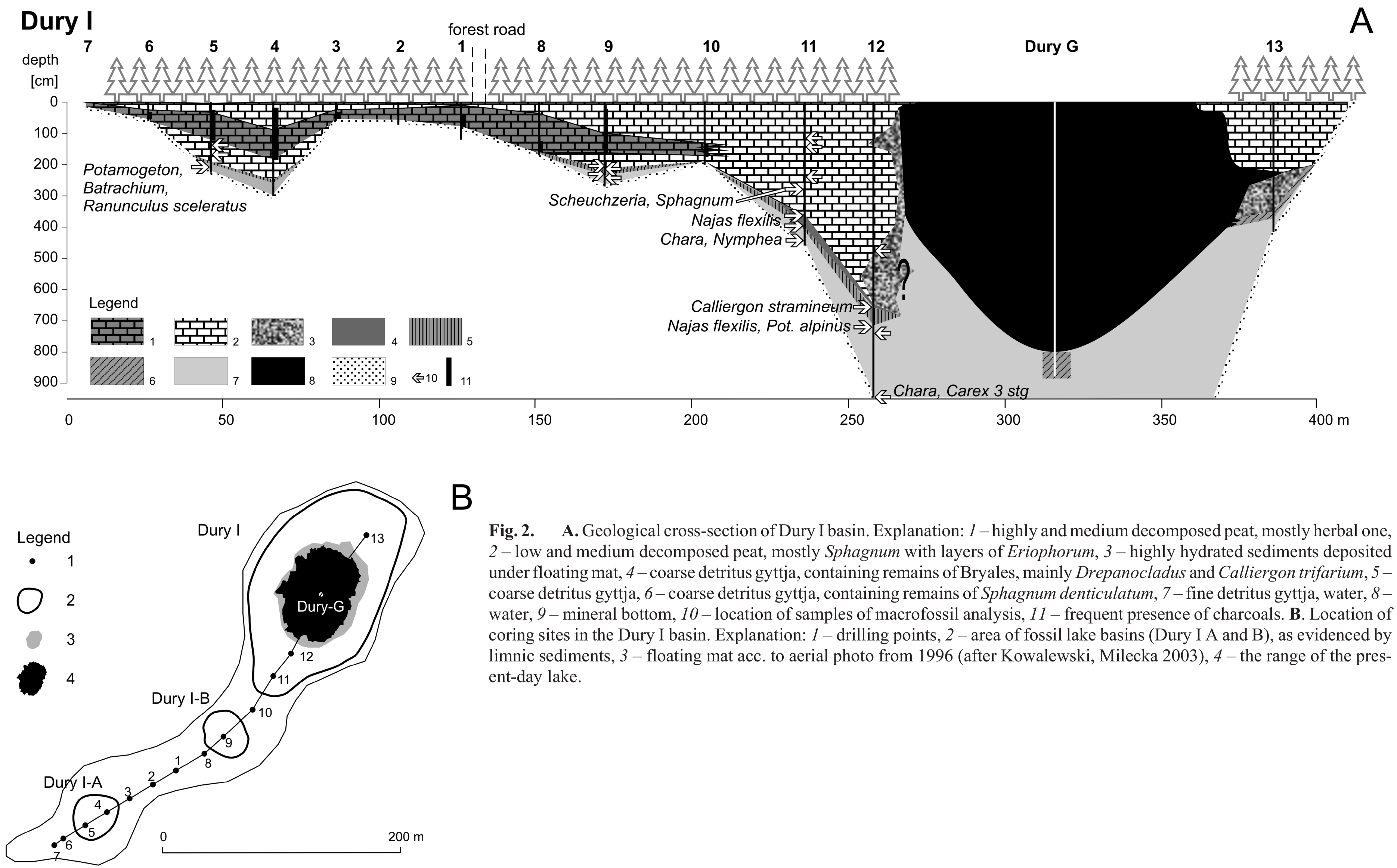


Fig. 2. **A.** Geological cross-section of Dury I basin. Explanation: *1* – highly and medium decomposed peat, mostly herbal one, *2* – low and medium decomposed peat, mostly *Sphagnum* with layers of *Eriophorum*, *3* – highly hydrated sediments deposited under floating mat, *4* – coarse detritus gyttja, containing remains of Bryales, mainly *Drepanocladus* and *Calliergon trifarium*, *5* – coarse detritus gyttja, *6* – coarse detritus gyttja, containing remains of *Sphagnum denticulatum*, *7* – fine detritus gyttja, water, *8* – water, *9* – mineral bottom, *10* – location of samples of macrofossil analysis, *11* – frequent presence of charcoals. **B**. Location of coring sites in the Dury I basin. Explanation: *1* – drilling points, *2* – area of fossil lake basins (Dury I A and B), as evidenced by limnic sediments, *3* – floating mat acc. to aerial photo from 1996 (after Kowalewski, Milecka 2003), *4* – the range of the present-day lake.

10 km south of Bytów. The Bytowskie Lake District physical-geographical mesoregion (Kondracki 2000) constitutes a lakeland, mainly composed of the Vistula glaciation Pomeranian Phase terminal moraines. The vast area of hills and hummocks, scattered or arranged in lines, usually exceeds altitude of 200 m a.s.l. Terminal moraines are dissected with numerous glacial channels in which lakes and peatlands occur. To the SE of the zone of the morain ridges, in front of its terminus, the Charzykowska outwash plain and Tuchola Forest are located, and the terrain gently slopes down to 150–130 m a.s.l.

In the moraine area of the highest hills of the Bytowskie Lakeland, a large number of peatlands occur, constituting small and deep basins, but usually not including gyttjas (specific kettle-hole peatlands). The relatively small area of 845 km^2 of the Bytowskie Lakeland includes as many as 1490 peatlands, mainly small, transitional, and raised bogs (77%). Detailed geobotanical studies on the peatlands were carried out by Jasnowska and Jasnowski (1981). They related this unique sedimentary patterns (*i.e.* absence of gyttja below *Sphagnum* peat) to the exceptionally developed relief and impermeable clayey ground. The feature typical of the region is the non-calcareous character of clays forming the moraine area.

Małe Leniwe peatland with the surface of 1.7 ha (including the lake) is located at the altitude of 177.0 m a.s.l. In its northern part, it is connected with significantly larger Duże Leniwe peatland with the area of several hectares (176.8 m a.s.l.). Duże Leniwe peatland is artificially drained to several closed-drainage basins with lower and lower bottoms (up to 170.5 m a.s.l.), located further north. To the south of the peatland, the altitude increases to 185 m a.s.l., and the terrain slopes down into Lake Rekowskie (162.5 m a.s.l.). Directly to the east and west of Małe Leniwe peatland, moraine hills occur, reaching up to 214 and 205 m a.s.l. According to the geological map 1: 200,000 Słupsk sheet (Mojski, Sylwestrzak 1975, Mojski *et al.* 1978), the entire area extending from Rekowo to the peatland, and further 3 km to the east, is covered with glacial till of the last glaciation Pomeranian Phase, with local additions of sands, gravels, and terminal moraine boulders. According to Marks *et al.* (2006), in the moraine area of the region, also kames and eskers occur.

METHODS

Geological drillings were carried out by means of an Instorf corer used for organic deposits, with a length of 50 cm and diameter of 45 mm. The deposits were described in the field according to the Troels-Smith system (TS system) (Tobolski 2000). Documentation concerning the drillings is in the home department of the first author. Drilling points were measured by means of a tape measure and GPSmap76. Based on the drillings, geological cross-sections were developed.

Selected 5 cm fragments of cores, mainly from the boundary zone of limnic and peat deposits of the Dury-I peatland, were analysed in terms of plant and animal macrofossils composition (18 samples with a total thickness of 90 cm). The material was sieved on 0.125 mm mesh sieves. The residue was sorted under a stereoscopic microscope Stemi 2000C by ZEISS in 10–100× magnifications. Selected macrofossils were transferred to Petri dishes into a mixture of distilled water, glycerine, and ethyl alcohol with addition of thymol (Tobolski 2000).

RESULTS

The geological study covered the area of peatlands adjacent to the centrally situated lake. The presence of lake deposits underlying peats confirms the limnic origin of the peatlands.

Geological structure and development of Dury I basin

Geological structure of the basin was described based on 13 cores retrieved from the peatland. Radiocarbon datings and a simplified version of geological cross-section were presented by Milecka and Kowalewski (2008, Fig. 2 therein). Studies on sediments filling Dury I basin revealed the past occurrence of 3 water bodies: the largest one, still existing today in the NE part, and two fossil water bodies in the SW part (Fig. 2).

The fossil Dury I-A basin is filled at the bottom with limnic deposits (medium detritus gyttja covered by a dozen or so cm layer of coarse detritus gyttja). The evidence of their occurrence are numerous findings of remains of aquatic invertebrates, particularly Chironomidae head capsules, Porifera gemmules, and Bryozoa statoblasts (macrofossil sample 210–215 cm, core D I-5). This medium detritus gyttja was further overgrown with roots and rhizomes of vascular plants, mainly sedges, growing here at a later stage. The gyttja included seeds and vegetative remains of *Potamogeton* sp. and *Carex* sp. 3-stg., as well as single seeds of *Batrachium* sp. and *Ranunculus sceleratus*, and branches with leaves of *Sphagnum* sect. Cuspidata. They document functioning of a shallow macrophytic lake, with moss cover, possibly developing on the shore.

Coarse detritus gyttja located above the medium detritus gyttja shows the occurrence of remains of both submerged aquatic and telmatic vegetation. It is covered by moderately decomposed peat formations. Macroscopic findings in the 167–173 cm sample (core 5) revealed the presence of eutrophic vegetation composed of Bryales, *Carex* sp. 3-stg, *Menyanthes trifoliata*, and *Thelypteris palustris*. The lake was surrounded by birch trees. In the consecutive macrofossil sample, located above (140–145 cm, core 5), *Menyanthes* does not occur any more. Only seeds of sedges and vegetative parts of *Thelypteris* remain. The next layer is composed of strongly decomposed peat with numerous charcoals, suggesting frequent fires. It underlies the living cover of the modern peatland.

In the Dury I-B basin, at the initial stage, fine detritus gyttja was deposited, as evidenced by the occurrence of remains of aquatic organisms, particularly Chironomidae head capsules and Porifera gemmules (macrofossil samples 236–241 cm and 223–229 cm, core 9). As opposed to lake I-A, no remains of submerged macrophytes were found. Birch and pine grew in the vicinity, represented by numerous remains (needles, seed coats, bud and seed scales, bark). Along with proceeding overgrowing of this shallow lake, it was filled with coarse detritus gyttja including numerous seeds of *Carex* sp. 3-stg and *Nymphaea alba*.

The water table was diminished by the encroaching vegetation, similar to that from lake I-A, resulting in development of a layer of moderately decomposed peat. In two macrofossil samples (211–216 cm and 204–209 cm, core 9), vast amounts of seeds of *Carex* sp. 3-stg and *Menyanthes trifoliata* were found. In the bottom sample, peat was mainly composed of remains of mosses from genus *Drepanocladus*, forming sedge moss peat. Above this peat layer, similarly as in lake I, a layer of strongly decomposed peat with numerous charcoals was deposited, covered by the modern acrotelm layer.

Lake basin Dury I-B reaches the maximum depth in core 9 (270 cm) (Fig. 2), and is separated from the main basin with a small mineral threshold with the ordinate of 193 cm below the level of the modern peatland (core 10). On the threshold, directly on the mineral bedrock, weakly decomposed herbaceous peat was deposited. No limnic deposits or sedge moss peat were found here, although core 8 still included them at a depth of 160 cm. In core 8, however, it is coarse detritus gyttja deposited on the slope of the basin. On the threshold, constituting an insignificant elevation between lake basin I-B and the main basin, conditions unfavourable for sedimentation must have occurred. On the other hand, their later erosion induced by fluctuating water table in the lake cannot be excluded with certainty.

In core 10, the last occurrence of moderately and strongly decomposed peat was recorded, thinning away in the NE direction. High degree of peat decomposition, and occurrence of numerous charcoals and larger pieces of wood suggests significant drying of the peatland.

The main basin, hereinafter referred to as Dury I, has not yet been entirely filled with deposits. The initial deposit accumulation occurred in the limnic environment. The bottom macrofossil sample from core 12 (941–946 cm) included vast amounts of wood (up to 20 mm in length and 5 mm in diameter) and well-rounded silica with heterogeneous grain distribution (up to 3 mm in diameter). Macrofossil findings, dominated by oospores of stoneworts, fruits of *Carex* sp. 3-stg, and statoblasts of *Cristatella*, document the earliest, shallow phase of development of the lake. Melting of blocks of dead ice resulted in its deepening and deposition of a thicker (over 200 cm) layer of fine detritus gyttja (uppermost sample from a depth of 730–737 cm, including numerous animal remains and pine remains) transitioning into medium and coarse detritus gyttja. Only in this layer, significant amounts of Cladocera post-abdomens were found.

In core 11, fine detritus gyttja was first deposited (bottom sample 440–445 cm), documenting a clear limnic stage in the basin development. A characteristic component of the deposit are oospores of stoneworts, occurring up to the top of the coarse detritus gyttja horizon. They are accompanied by numerous seeds of *Nymphaea alba*.

The bottom of the coarse detritus gyttja layer located above is represented by sample 395–400 cm, where very rich macrofossil findings were recorded. Stoneworts and *Nymphaea alba* continue to occur here, and *Carex* sp. 2- and 3-stg appear in large numbers. Submerged macrophytes, along with stoneworts, are represented by several species of *Potamogeton* and *Najas flexilis*. Brown mosses occur in large numbers, particularly *Calliergon trifarium*, *Mesea triquetra*, and genus *Drepanocladus*. Apart from the autochthonous elements specified above, the sample included significant amounts of allochthonous elements: remains of pine (needles, bark, seed coats, bud and seed scales) and birch (fruits and fruit scales). Remains of different small aquatic invertebrates occurred in insignificant numbers.

The sample representing the top of coarse detritus gyttja (360–365 cm) included similar findings as the sample described above, but remains of autochthonous organisms occurred in substantially smaller numbers. Occurrence of seeds of *Potamogeton*, *Najas*, and *Nymphaea alba* was sporadic, similarly as that of oospores of stoneworts. Among mosses, *Sphagnum* sec. Cuspidata was predominant, although brown mosses still occurred, including *Calliergon trifarium*. In the layer located above (from 260 cm), moss peat with *Eriophorum* predominated.

Findings analogical to those described above were determined in macrofossil samples in core 12 (715–720 cm – fine detritus gyttja, and 650–655 – Turfa bryophytica (Call.)), although due to a larger distance from the shore, remains of pine and birch were scarce. In sample 715–720 cm, remains of *Potamogeton* (compare similar findings by Kowalewski, Milecka 2003, Dury I, horizon 735–897 cm) and *Najas flexilis* were predominant. Proportion of mosses was insignificant. In sample 650–655, almost the entire sediment was composed of stems with leaves of *Calliergon trifarium* (compare similar findings by Kowalewski, Milecka 2003, Dury I, horizon 627–684 cm). Due to the lack of limnic accumulation indicators, the sediment was determined as moss peat (Tb4 (Call.)). Higher up, (484–645 cm) very loose and strongly hydrated sediments occurred, including numerous peat elements. During the field works, they were described as gyttjas due to their structure. They constitute a classic case of a formation of mixed sedimentation-sedentation origin (Kowalewski 2009), similarly as the thin layer from a depth of 40–53 cm, and deposits determined in a core on the other side of the lake from a depth of 200–350 cm (Fig. 2).

Compacted *Sphagnum* peat in a macrofossil sample occurred for the first time in the macrofossil sample located 2 m higher, at a depth of 470–475 cm, where peat was composed of *Sphagnum* sect. Cuspidata. It included seeds of *Eriophorum vaginatum* L., pine, and *Scheuchzeria palustris*. Also vegetative remains (hydatodes) of the latter were preserved. In core 11, Scheuchzeria-Sphagnum peat was found in a sample from a depth of 275–280 cm. It was dominated by vegetative (fragments of leaf sheaths, hydatodes) and generative (seeds) remains of *Scheuchzeria palustris*. Remains of pine were numerous. The same type of peat was recorded in the consecutive macrofossil sample (243–247 cm).

In the next examined sample (145–150 cm), *Sphagnum* peat with addition of vegetative remains of *Eriophorum vaginatum* L. was deposited. The latter predominated in the consecutive sample located above (110–115 cm). The deposit was mainly composed of remains of rhizomes of *Eriophorum vaginatum* L. Occurrence of its spindles was also abundant. Apart from *Eriophorum vaginatum*, also remains of *Sphagnum* and seeds of *Andromeda polifolia* occurred. A feature typical of the sample was high amount of charcoals.

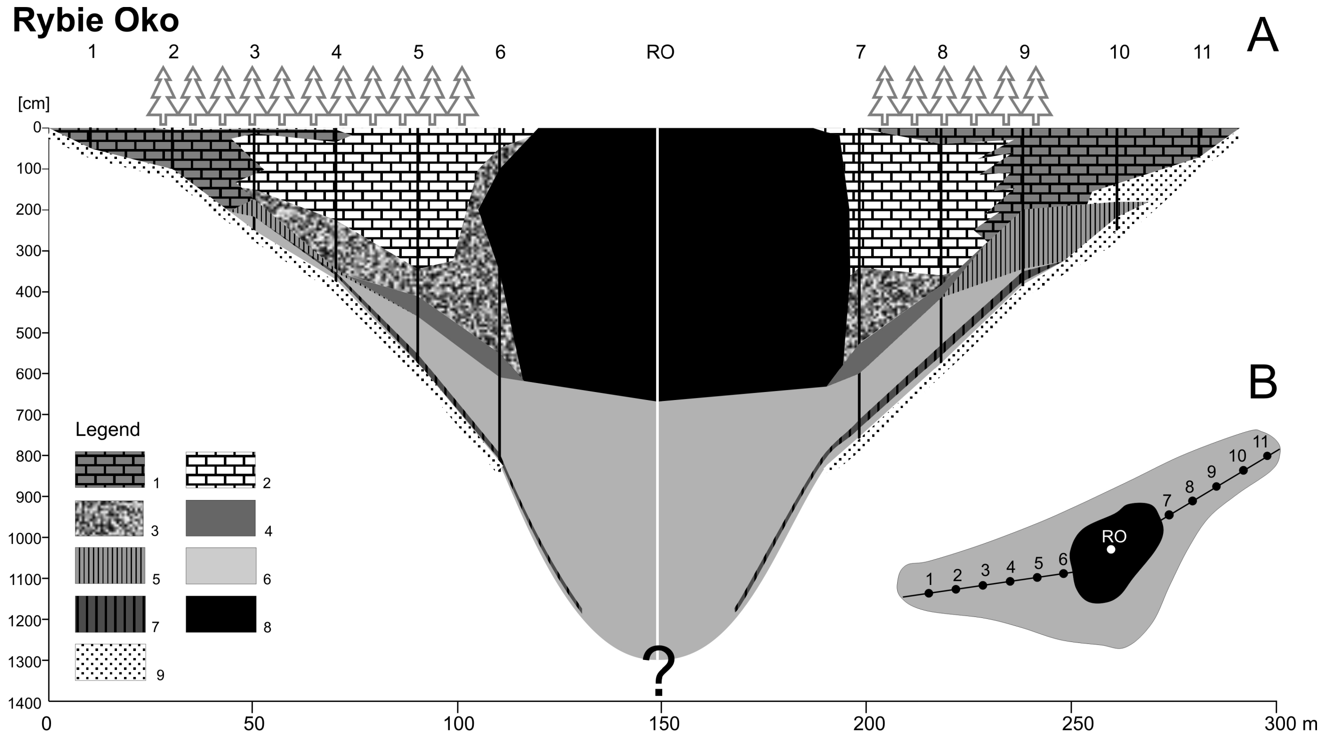


Fig. 3. **A.** Geological cross-section of Rybie Oko basin. *1* – highly and medium decomposed peat, mostly herbal one, *2* – low and medium decomposed peat, mostly *Sphagnum* with layers of *Eriophorum*, *3* – highly hydrated sediments deposited under floating mat, *4* – coarse detritus gyttja, containing remains of Bryales, mainly *Drepanocladus* and *Calliergon trifarium*, *5* – coarse detritus gyttja, *6* – fine detritus gyttja, water, *7* – bottom organic layer, *8* – water, *9* – mineral bottom. **B.** Location of coring sites in the Rybie Oko basin. Explanation: grey colour – mire, black colour – lake, black dots – coring sites.

Geological structure and development of Rybie Oko peatland

The geological structure of the peatland was described based on 11 cores performed on the peatland, and one core sampled at a depth of 6.2 m from the central part of the lake (Fig. 3). The first version of the geological cross-section, and photographs of selected sediment cores are published by Tobolski *et al.* (2006, p. 168). The deepest drilling from the peatland (core 6) has a depth of 8.4 m, reaching the bottom. The sediment core from the lake (RO), with a length of 700 cm, documents deposition of sediments to a depth of 13.2 m, reaching the Late Glacial age (Tobolski *et al.* 2006, p. 169). This core almost reaches the bottom of the basin.

The type and distribution of deposits in Rybie Oko are similar to those from Dury I. Contrary to results from DURY I, however, the basin developed in the form of a single depression with irregular shape. Therefore, it can be compared only to the main basin of DURY-I.

Sands with an admixture of organic matter staining them grey or graphite, are covered by organic layers including numerous charcoals. Their thickness does not exceed several cm, and usually amounts to 1 cm only. On those layers, after a rapid deepening of the lake, fine detritus gyttja was deposited, reaching a thickness of a dozen or so cm. It is covered by the same gyttja, but including a significant addition of fine-grained silica (Argilla granosa [Ag] in the TS system), and sometimes sand (Grana [G] in the TS system). They may constitute evidence of a Younger Dryas cooling, and reach a thickness of even several tens of cm.

At the beginning of the Holocene, slow sedimentation of fine detritus gyttja commenced, transformed in the zone closer to the shore into shallow-water gyttjas rich in detritus. In the central zone of the lake, its sedimentation still continued. Along with the proceeding overgrowing of the lake, fine detritus gyttja was transformed into coarse detritus gyttja. It included remains of both submerged macrophytes (genus *Potamogeton*) and species typical of meso-eutrophic floating mat (*Menyantes trifoliata*). The last stage of lake disappearing, similarly as in core 12 in Dury-I, form a layer including numerous Bryales mosses, including genera *Drepanocladus* and *Calliergon trifarium*. This layer was the thickest in the cores located closer to the lake.

Consecutive layers of the sediments are, at least in the coastal zone of the lake (core 6), strongly hydrated and very loose, constituting a transitional zone of limnic accumulation occurring under the floating mat. It can be described as "floating remains of organic matter". In cores 3–5 and 7–9, located further from the lake shores, the sediment was described as "remains of floating mat" or "peat under floating mat" with varying colour and horizontal distribution of remains, suggesting deposition in water. They all constitute a classic example of sediments of mixed origin, developed under floating mat (Kowalewski 2009).

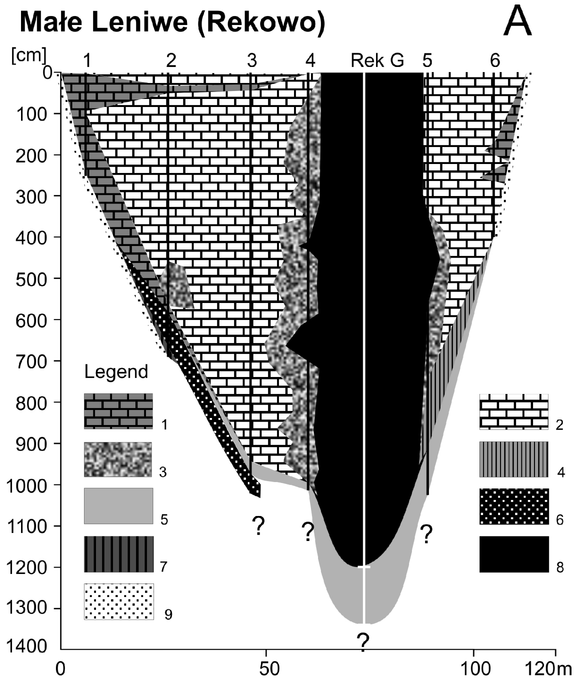
The last layer, the thickest in majority of the cores analysed, is composed of *Sphagnum* mosses (Tb(Sph.)) interspersed with a layer of herbaceous-*Eriophorum* peats (Th (Erioph.)). Locally, those peat deposits were difficult to distinguish macroscopically from detritus gyttjas (frequent record in field description: "gyttja structure"). This layer also included remains of heathers (Ericaceae). Closer to the basin boundaries, the surface layers are composed of moderately and strongly decomposed herbaceous peat, with predomination of the latter, particularly in boundary cores (1–2 and 10–11).

Geological structure and development of Małe Leniwe (Rekowo) peatland

The geological structure of the peatland was described based on 7 core profiles performed on the peatland (Fig. 4A). The deepest cores (cores 3–5) reached a depth of 10 m, not reaching the bottom of the basin. A sediment core with a length of 140 cm (Rek-G), taken from the lake (1200–1340 cm), documents a layer of coarse detritus gyttja. The depth of the basin is unknown.

The peatland is located in a deep depression with strongly inclined eastern and western slopes. The difference between its bottom and the most elevated point of the catchment amounts to about 50 m. To the south of the basin, the terrain gently slopes up, and in its northern part, Rekowo peatland is connected with a large basin filled with peats surrounding Lake Leniwe (Fig. 4B). Core ML7, taken from the narrow passage between Rekowo and Leniwe peatlands, revealed the occurrence of a mineral ridge under peat, located between the peatlands at the ordinate of 380 cm. The uppermost layer included *Sphagnum*-*Eriophorum* peats, reaching a depth of 270 cm. Below, deposition in a more hydrated environment occurred, as evidenced by the horizontal distribution of epidermises in peats at a depth of 280–300 cm.

Sediments documenting deep-water sedimentation (fine detritus gyttjas) were determined only below a depth of 9 m. Therefore, they occur only in the central part of the basin (cores 3–5). At the bottom of the layer, gyttja locally included sands and clays. In the remaining geological cores,



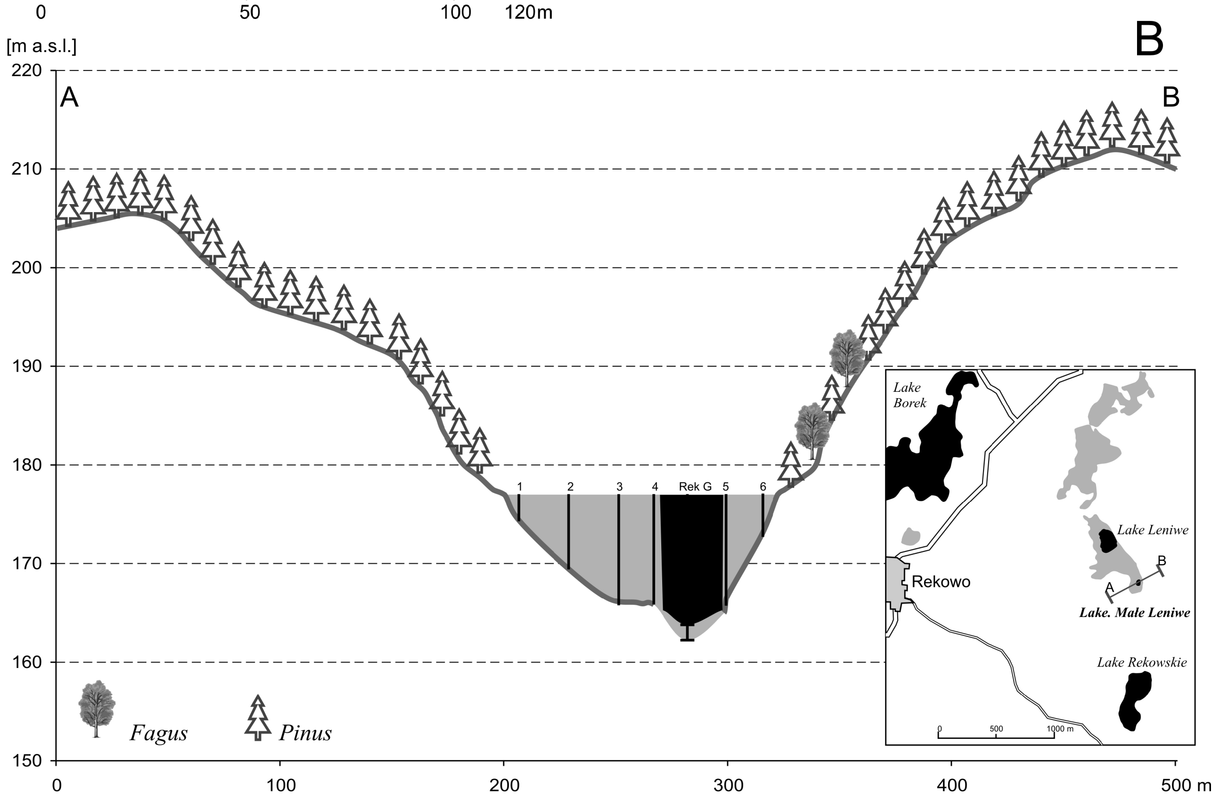


Fig. 4. **A.** Geological cross-section of Małe Leniwe (Rekowo) basin. *1* – highly and medium decomposed peat, mostly herbal one, *2* – low and medium decomposed peat, mostly *Sphagnum* with layers of *Eriophorum*, *3* – highly hydrated sediments deposited under floating mat, *4* – coarse detritus gyttja, *5* – fine detritus gyttja, *6* – mineral-organic matter, *7* – silt , *8* – water, *9* – mineral bottom. **B.** Topographic sketch A–B through Małe Leniwe lake basin and surrounding moraine hills: grey colour – body of the mire, black colour – water body of the lake. Coring points were located along the profile. In the inset: location of the sketch – grey colour – mires, black colour – lakes.

mineral-organic formations of unknown origin occurred (Fig. 4A).

The formations are covered by a layer of moss peat, developed by *Sphagnum*, *Eriophorum vaginatum* and heathers Ericaceae. Remains of birch and pine were numerous, particularly needles, leaves, branches, and bark.

In almost all of the cores (except one), occurrence of strongly hydrated peat was noticed, with predominance of *Sphagnum* remains. These remains were often deposited horizontally, suggesting aquatic accumulation environment in which hollow peat develops (compare Jasnowski 1962). The same was determined even in core 6, located near the eastern shore. Strongly hydrated sediment of mixed origin (developed in water, but dominated by *Sphagnum* remains) was found in cores 2, 3, and 5, and was dominant in core 4. In part of core 5 (740–912 cm), its composition was different, dominated by allochthonous elements: leaves, branches, bark, and needles.

DISCUSSION

The geological study carried out revealed the relationship between depositional processes and (1) morphometry of basins, (2) type of catchments and (3) developmental pathways of the lake. The common element of the lakes studied is the occurrence of floating mat encroaching the water table.

Morphology of modern peatland-lake ecosystems in outwash plain and moraine areas is varied: on the outwash plain, they are more shallow and larger, on the moraine – deeper and smaller (Banaś 2010). These differences, however, concern mainly morphology of the present water body (not the basin) whereas the mechanism of floating mat growth and deposition process are similar. Małe Leniwe peatland occupies the area of only 1.5 ha, and the lake – 0.01 ha, reaching a significant depth of 12 m (determined in accordance with the depth of the uppermost sediments during sampling by means of a gravity probe in March 2007 at the water level higher than during measurements carried out in summer – compare Banaś 2010). The basin has a shape of a steep cone (Fig. 4), and the peat walls forming the basin of the modern lake are virtually vertical, forming a cylindrical shape. The depth index (average depth/maximum depth) of the lake, assuming data following Banaś (2010), is estimated at the level of 0.93 (10.9/11.7 m), ranking it the second in Poland after Lake Płociczno (Choiński 2007). Small, deep basins of this type, filled with waters of lakes or organic deposits, are very numerous on the Bytowskie Lakeland (Jasnowska, Jasnowski 1981). According to the classification of peatland basins by Jasnowska, Jasnowski (1981), the basin analysed belongs to the category of small basins (below 5 ha), usually with no limnic sediments at the bottom. The depth of the basin of Małe Leniwe is significantly higher, however, than the average for the above mentioned peatlands on the Bytowskie Lakeland, due to which the lake and deposition of limnic sediments at the bottom survived until modern times. Peatland-lake ecosystems with a similar depth in the belt of Pomeranian moraines (Żurawie Chrusty – depth of 16 m and Kumki Małe – 10.5 m) are discussed by Banaś (2010). Basins of lakes located on the outwash plain (Rybie Oko and Dury I) are not as steep, but are also cone-shaped, with an accompanying shallow lip in the case of Lake Dury I. The shape of their modern lake basins is determined by peats filling the basin, forming vertical side walls with a height of 2–3 m. Occurrence of vertical walls results in a very high depth index also for those lakes. According to data by Banaś (2010), for Lake Rybie Oko, it amounts to 0.78. The fact of occurrence of water pockets under floating mat is also significant, forming the lake not in a shape of a cylinder, but a cylinder with a truncated cone at the bottom (Banaś 2010).

The maximum depth of the basins of the systems studied reaches at least 13–14 m. In the authors opinion, the value can be used as a reference minimum depth of a basin enabling survival of a lake until modern times. The rate of filling the basin with gyttja depends on the lake productivity. In accordance with the glacial-interglacial cycle, productivity of lakes within catchments poor in biogenes (discussed in this paper) should decrease as a result of washing out biogenes from the catchment, and simultaneous acidification process. The latter process also has a decisive effect on development of floating mat. The precondition for floating mat development is also survival of the lake with no development of telmatic assemblages in the littoral. Their growth significantly accelerates the process of disappearing of a lake and its transformation into a peatland. A large number of lakes (with origin analogical to that of the lakes studied) entirely grown over are known, with a depth not exceeding 10 m (*e.g.* Kowalewski *et al.* 2002, Lamentowicz 2005, Gałka 2007). Assuming the average rate of accumulation of peats and gyttjas at the level of 0.5–1 mm/year (Żurek 1986), majority of such lakes disappeared entirely from the landscape. Therefore – taking into consideration the low productivity of lakes located in nutrient poor catchments – depth significantly exceeding 10 m seems to be a condition necessary for a lake not to be subject to total terrestrialisation. Similar results were obtained by Bunting, Warner (1998), analysing several tens of small lakes and peatlands in southern Ontario. The thickness of organic deposits of the peatlands amounted to 3–10 m, and the thickness of limnic deposits in lakes overgrown with floating mat amounted to 5–9 m, with the depth of the basin reaching 6–12 m. Such a low rate of sedimentation must have been determined by low productivity of the lake ecosystem, favoured by acidic conditions. In the conditions of acidic lakes, the rate of decomposition decreases (Wetzel 1975), but also productivity is a subject to decrease. It is confirmed by the low rate of sedimentation in Dury I throughout the last 2200 years, estimated at the level of only 0.4 mm/year (Milecka, Kowalewski 2008). Therefore, the faster the lake becomes subject to invasion by *Sphagnum* floating mat and related acidification, the longer it will be able to survive. Floating mat in the system has the function of preserving the lake, preventing its rapid overgrowing.

A significant factor favouring development of floating mat is the considerable inclination of the sides of the lake basin. According to Moore (2008, p. 102) "the steepness of the sides of the lake may make it impossible for marginal vegetation to invade, because the water is too deep for them to take root in the bottom sediments, but it is possible for invasion to take place as a result of extension of floating rafts from the lake edges". This statement challenges Bunting and Warner's (1998, p. 10) point of view, who suggest that "the presence of a shallow lip where wetland development can occur, provides a source for the mat forming species". Our opinion supports the former idea, and contradicts the latter. Shallow lips occur only in Dury I basin, and they did not favour development of floating mat due to excessive invasion of macrophytes rooted in the bottom. In the remaining lakes, only in the zone located the nearest to the mineral shore remains of herbaceous vegetation were found, suggesting occurrence of emerged vegetation (rooted in the bottom) in the past. The steepness of the slopes of the basin is a factor favouring development of floating mat not only in the spatial, but also temporal aspect. It results from the fact that floating mats developed rather in the younger part of the Holocene, in accordance with the glacial-interglacial cycle (Birks 1986, Tobolski 1976). Therefore, for a long time (until the Subboreal period), the lake must have had clear shores devoid of coastal vegetation functioning as a filter of supplied humic acids, not allowing for the lake acidification and development of floating mat. A similar situation occurs in Lakes Małe Łowne (Kowalewski *et al.* 2009) and Dury V (Kowalewski, Barabach 2010). Such conclusions are also confirmed by common associating peatland-lake ecosystems with the geomorphological form of kettles which, as the name itself suggests, usually have steep sides. On the other hand, it should be remembered that the presence of a narrow belt of macro- phytes (*e.g.* sedges) counteracts increase in water trophy, creating a buffer zone seizing biogenes inflowing from the catchment, therefore slowing the process of filling the basin and disappearance of the lake.

Development of floating mat is accompanied by sedimentation of gyttja with very loose structure. Bunting and Warner (1998) describe this type of lake bottom as "false bottom". Non-consolidated bottom also makes it impossible for macrophytes to take root, even in the conditions of increased trophy of the lake, providing more favourable conditions for floating plants.

Another factor favouring development of floating mat is the non-calcareous character of landforms of the catchment. Calcium fertilises soil and water, and counteracts their acidification. Outwash plain areas, composed of sands, are usually devoid of calcium carbonate. Similarly, a feature typical of the moraine area of the Bytowskie Lakeland is the non-calcareous character of its landforms (Jasnowska, Jasnowski 1981).

Development of the lake

The bottommost deposits of the basins studied in the area of the outwash plain include fine sands. Admixture of mud or clear muds were determined only in Małe Leniwe, located in the moraine area. In all the basins in bottom mineral formations, a significant addition of organic matter was determined. Such a character of sediments corresponds with the general record of bottom sediments of thaw lakes, recorded in the Young Glacial area (Błaszkiewicz 2005).

The water table of Dury I basin during the Holocene was similar to that of today or lower by no more than 1 m. It is evidenced by findings of remains of submerged macrophytes (*Potamogeton*) and remains of accompanying invertebrates (Porifera, Bryozoa) from a depth of 210–215 cm of core Dury I-5, and deposition of fine and medium detritus gyttja in fossil basins A and B. Basins A and B are separated by a mineral threshold with the ordinate of only 60 cm (cores 2 and 3) below the modern surface of the peatland. This restricted movement of water between basins A and B, whereas basin B, constituting one body with the main basin, was prone to wave shoaling. The fact explains the occurrence of remains of aquatic and telmatic macrophytes at the bottom of sediments in basin A, and their somewhat later deposition (in terms of depositional processes) in basin B, where conditions were less favourable for colonisation by macrophytes.

From the beginning of its development and throughout the major part of its history, basin Dury I functioned as a mesotrophic lake, with at least neutral reaction. Such conclusions are derived from the bioindicative significance of limnic findings in basins A and B, and occurrence of remains of macrophytes requiring non-acidic conditions (*Najas flexilis*) at the top of the gyttja in the main basin. Increased water fertility is also suggested by high participation of *Pediastrum* sp., ending along with growth of floating mat on the lake surface (Kowalewski, Milecka 2003). Sedimentation rate until the end of the Atlantic period was low (core 11 and 12), although may also result from the inclination of the slopes of the lake basin (Fig. 2). Also in Lake Małe Leniwe, limnic sedimentation rate was low. It is suggested by non-published results of pollen analysis of core Małe Leniwe G (Tobolski – oral information).

The bottom of Lake Dury I was overgrown by numerous submerged macrophytes, such as *Chara* sp. and *Potamogeton* sp., suggesting good light in water column. Characeae as a pioneer community was found in Lake Jezioro also surrounded by floating mat (Nita, Szymczak 2010). Nympheids were represented by *Nymphaea alba*. At the final stage of limnic sedimentation, succession of *Najas flexilis* occurred. The limnic stage ends with growth of floating mat. Its age, based on comparison of the lithology of core 12 and core Dury I (Kowalewski, Milecka 2003), can be estimated at the beginning of the Subboreal period. Until the end of the climatic optimum, Lake Dury I (the main basin) functioned in changing conditions to little extent. From the beginning of its development, submerged macrophytes occurred there in large numbers. In the climatic optimum, it was probably somewhat shallower than today. Numerous remains of *Najas flexilis* were found at a depth of 715–720 cm, whereas the optimum of its occurrence amounts to 2 m, reaching the maximum depth of 6 m (van de Weyer 2005). *Najas flexilis* is a species with a wide ecological amplitude, but diminishing in Europe due to deterioration of climatic (cooling) and edaphic conditions (water acidification, modern pollution), and low competitiveness (*e.g.* 1975, Zalewska-Gałosz 2001). Diminishing of *Najas flexilis* usually occurred after climatic optimum, approximately 5,000 BP.

In the changed climatic conditions of the Subboreal period, *Sphagnum* mosses were introduced into floating mat, causing gradual acidification of the lake water, leading to a radical change in the occurring environmental conditions. At least from approximately 2200 BP (Milecka, Kowalewski 2008), the lake has been inhabited by acidophilic mosses (*Sphagnum denticulatum*). Succession of mosses in peatland-lake ecosystems is a typical phenomenon. Currently, lakes surrounded by floating mat are acidic (Banaś 2010), with the bottom covered with *Sphagnum* sp. and *Warnstorfia*. The plants grow at a depth of 3–5 m, exceptionally up to 7 m. *Sphagnum denticulatum* (= *S. auriculatum*) and *Warnstorfia exannulata* (=*Drepanocladus exanulatus*) grow at the highest depths, with the latter usually constituting an addition.

Probably earlier, as the only one of the lakes analysed so far, two small fossil water bodies in basin Dury I were subject to disappearing (Fig. 2). It occurred as a result of overgrowing by meso-eutrophic assemblages, including numerous *Menyantes trifoliata*, *Carex* sp., and *Thelypteris palustris*. The occurrence of eutrophic species suggests that it took place rather before development of *Sphagnum* floating mat on the main basin, and acidification of the entire water body. The direct cause of overgrowing was the presence of a shallow lip in the south-western part of the basin, favouring the development of emergent plants. Such sediments are not encountered in the remaining basins, where due to the conical shape of the basin, peatland vegetation could develop only along the narrow belt along the lake shore. The least favourable conditions for development of surface-floating vegetation occurred in the basin of Lake Małe Leniwe with steep slopes.

A layer of strongly decomposed peat was found only on the completely terrestrialised part of basin Dury I, which suggests water level variations in the past, reaching, according to lithological evidence, at least 1 m below today's water level. The dry event can be correlated with the Atlantic period (around 6000–8000 BP), because growth of floating mat and development of layers of *Sphagnum* peat lying on strongly decomposed peat must have occurred only after acidification of the entire water body. The dry event from the region of Tuchola Forest is cited by a number of authors (*e.g.* Ralska-Jasiewiczowa 1989, Żurek, Pazdur 1999, Lamentowicz *et al.* 2008).

Sedge-moss floating mat, (Bryaleti sedge moss peat with *Calliergon trifarium*, *Mesea triquetra* and *Drepanocladus* sp.), growing over the main basin of Lake Dury I, although of entirely different character than currently functioning *Sphagnum*-moss floating mat, is recorded in the peat-gyttja interface in a number of stratigraphic series from fossil lakes overgrown by floating mat in the past (*e.g.* Wąs 1957, Jasnowski 1957a,b, 1959, Lamentowicz 2005). Currently, assemblages of this type are very rare (Jasnowski 1959), which also seems to be conditioned by the climate.

On the sedge-moss floating mat, succession of *Sphagnum* occurred, leading to development of *Sphagnum*-peats. A feature typical of sediments deposited in water bodies with floating mat is occurrence of strongly hydrated sediments including peat elements deposited in the limnic environment (Kowalewski 2009). Remains of mosses are, therefore, often distributed horizontally, which can be mistaken with deposits created in peat hollows, described among others by Jasnowski (1962) from the Ziemia Szczecińska region. This author indicates peat developed with predomination of *Sphagnum recurvum* as analogical to the currently developing systems with *Sphagnum* floating mat, and secondary deposits in exploitation pits. The occurrence of those strongly hydrated structures located among and under peats is highlighted in the geological section. They are the most abundant under the floating mat in the western part of Lake Małe Leniwe. Their basic component is *Sphagnum* with admixture of remains of herbaceous plants (remains of *Eriophorum* and heathers) with TS formula of the type Tb4Th+ – Tb3Th1. Peats deposited closer to the sides of the basin are more dense and compacted. The asymmetry of filling the eastern and western part of the basin is worth attention. The deepest place is probably located on the axis of core 4. In this situation, the shift of the lake to the east is interesting. Perhaps it is related to the activity of dominant western winds, hindering growth of floating mat in the eastern direction (Crum 1988). Strongly hydrated and loose formations deposited under floating mat are described in the literature as debris peat (Kratz, DeWitt 1986), Sinktorf (German term; Succow, Joosten 2001), or peaty gyttja (Winkler 1988).

Occurrence of strongly hydrated formations deposited under floating mat also influences development of pine forest on floating mat (Kowalewski, Barabach 2010). Deposits of the peatland surrounding Lake Małe Leniwe are hydrated to the largest extent. Therefore, only single pines occur there. The area of the passage to Lake Leniwe, located further north, is overgrown to a larger extent. In winter, the water level increases significantly, flooding even fragments of a road along the peatland. The basins Dury I and Rybie Oko are overgrown in the major part of their area by marshy coniferous forest with *Ledum palustre* L. and *Eriophorum vaginatum* L. The area free from trees is located only in the narrow belt of floating mat around the lake. Also the tree line zone is uncovered, as well as the adjacent area with *Eriophorum vaginatum* in Rybie Oko, although it was quite dried in the study period. The floating mat on Rybie Oko is somewhat more eutrophic than in Dury I, where no eutrophic species are encountered, such as *Lysimachia thyrsiflora* growing in Rybie Oko.

CONCLUSIONS

Functioning of *Sphagnum* peatland-lake ecosystems should be considered in the wide context of allo- and autogenic processes (Bunting, Warner 1998, Korhola 1995). Initially, development of the system is determined by the ecological type of the catchment and the lake itself. Both the elements, however, are subject to spontaneous (autogenic) alterations triggered by external (allogenic) influences. Conditions favouring development of floating mat are mainly location of the lake in a sandy (determines insignificant supply of biogenes, preferring low nutrient demanding species), non-calcareous (calcium prevents acidification of the environment) catchment overgrown by coniferous forest (supports production of humic acids), and steepness of the lake basin, that prevents development of telmatic vegetation which would make development of floating mat impossible. The initial succession of floating mat is, therefore, determined allogenically (influences from the catchment), and its main causes are supplies of humic acids to the lake from the catchment of the pine forest. Once initiated, however, it induces autogenic alterations, causing another increase in water acidification, affecting the ecological type of the basin, and the inhabiting specific vegetation assemblages. A model case is development of Dury I, where the basin initially inhabited by species not favouring acidic conditions (*Najas flexilis* and *Chara* sp.) was subject to transformation into a strongly acidic lake – a habitat for acidophilous mosses. The direct cause for the alteration was influence of *Sphagnum* floating mat vegetation, acidifying the lake waters, therefore an autogenic factor. It is in accordance with the general model of lake succession by Wetzel (1975), who indicates domination of autochthonous factors at the initial stage of development of the lake, dominated by planktonic succession and growing participation of the allogenic factor (succession of littoral vegetation) along with the lake development.

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