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An over 200-Year Environmental Change Record from the Highly Impacted Small, Hardwater Lake Pniówno (Chełm Hills)

Ponad 200-letni zapis zmian środowiska w osadach małego, twardowodnego jeziora Pniówno (Pagóry Chełmskie)

Abstrakt: Artykuł przedstawia wyniki analiz paleoekologicznych i chemicznych osadów dennych małego, twardowodnego jeziora Pniówno. W profilu o niezaburzonej strukturze zanalizowano zmiany składu subfosylnej fauny wioślarek (Cladocera, Crustacea), oznaczono zawartość węgla organicznego, węglanów i krzemionki (z wydzieleniem frakcji terygenicznej i biogenicznej) oraz wiek osadów za pomocą datowania metodą ^{210}Pb. Dodatkowo, w oparciu o mapy archiwalne, przeanalizowano zmiany sieci wód powierzchniowych i użytkowania zlewni w okresie od początku XIX w. po czasy współczesne. Mimo powszechnego poglądu o pogarszającym się stanie wód powierzchniowych na skutek wzrostu presji antropogenicznej w okresie objętym analizą stwierdzono okresową poprawę stanu wód, którego przyczyną były najprawdopodobniej zmiany hydrologiczne i klimatyczne, umożliwiające rozwój roślinności zanurzonej, a także pustka osadnicza spowodowana działaniami podczas I wojny światowej.

Słowa kluczowe: subfosylne szczątki Cladocera; jezioro Pniówno; Pagóry Chełmskie; paleolimnologia; jakość wód; wpływ człowieka; Mała Epoka Lodowa

Abstract: The paper presents the results of paleoecological and chemical analyzes of bottom sediments of the small hardwater lake Pniówno. In the sediment profile of undisturbed structure, remains of subfossil Cladocera were analyzed, as well as the content of total organic carbon, carbonates and silica (with separation of terrigenous and biogenic fractions). The age of sediments was determined by dating with the ^{210}Pb method. In addition, changes in the surface water network and catchment area were analyzed based on archival maps, covering the period from the beginning of the 19th century to modern times. Despite the widespread view of the deteriorating state of surface waters as a result of increased anthropogenic pressure, the example of the shallow Pniówno Lake indicates a periodic improvement in the state of water during the time covered by the analysis. This was probably caused by hydrological and climatic changes enabling the development of submerged macrophytes as well as settlement decline during the First World War.

Keywords: subfossil Cladocera remains; Lake Pniówno; Chełm Hills; paleolimnology; water quality; human impact; Little Ice Age

INTRODUCTION

For the effective protection, management and sustainable use of lake ecosystems, vast knowledge on its functioning, as well as on the abiotic and biotic factors of its development are necessary (Smol 1992; Hennebelle et al. 2018). For this purpose, it is important to use long-term monitoring data covering periods when climatic and hydrological conditions or anthropogenic pressure had changed (Froyd, Willis 2008). However, due to the limited availability of instrumental monitoring data, in particular in relation to smaller lakes that are not covered by any form of protection, using proxy data that provides indirect information about changes of water quality and functioning of lake ecosystem might be the only way (Battarbee et al. 2005). Lake sediments provide a valuable insight into long-term changes within lakes and their catchments – these natural archives constantly record variation inside lakes and in their surroundings. Such change can be track further and interpreted by means of paleolimnological methods (Oldfield 1977).

The study presents the results of paleolimnological analysis (subfossil Cladocera, sediment chemistry) of sediment samples from a small, hardwater lake – Lake Pniówno. This lake, up to the first decade of the19th century, was one of the less studied among the so-called Łęczna-Włodawa lakes (Ferencz, Dawidek 2014). Indeed, only Radwan et al. (1971; 1972; 1973) provide some hydrochemical data roughly characterizing the state of the lake in the mid-1960s. Also, little is known about the aquatic biocenosis of Lake Pniówno, as, since the studies of Kowalczyk (1977), no data have been published on the zooplankton composition of this waterbody, and the only data concerning macrophyte vegetation are given by Fijałkowski (1959) and further by Sugier et al. (2010).

Given the above, the main aim of the study was to trace changes in the ecological status of lake-catchment geo-ecosystem of Lake Pniówno, provided by paleolimnological proxies (Cladocera, sediment chemistry). Subfossil Cladocera remains are known to be a valuable source of information regarding such limnological parameters as climate, trophy of waters, lake level fluctuations or habitat diversity, including aquatic vegetation (Alhonen 1970; Korhola et al. 2000; Chen et al. 2010; Liu et al. 2014; Nevalainen et al. 2012). The insight into factors of the observed changes was derived mainly based on analysis of the catchment hydrological and land-use alterations of archive maps.

REGIONAL SETTINGS

The small, shallow, polymictic Lake Pniówno (51°14’47”N, 23°20’32”E) is one of the Łęczna-Włodawa lakes – a unique group of 67 lakes located in Eastern Poland, over 200 km outside the range of the last glaciation. Their non-glacial origin makes the Łęczna-Włodawa lakes distinctive among the vast majority of Polish lakes. Located at southernmost peripheries of the group, Lake Pniówno is in the borderland of the Cretaceous Chełm Hills (part of the Polish Uplands) and the Polish Lowlands (Fig. 1). This lake, together with the nearby situated Słone, Syczyńskie and Tarnowskie lakes, are often considered as a distinctive sub-group among the Łęczna-Włodawa lakes, mostly due to their high quantity of the underground water supply and the hydrochemical properties of the lake waters (Dawidek 1998; Ferencz, Dawidek 2012).

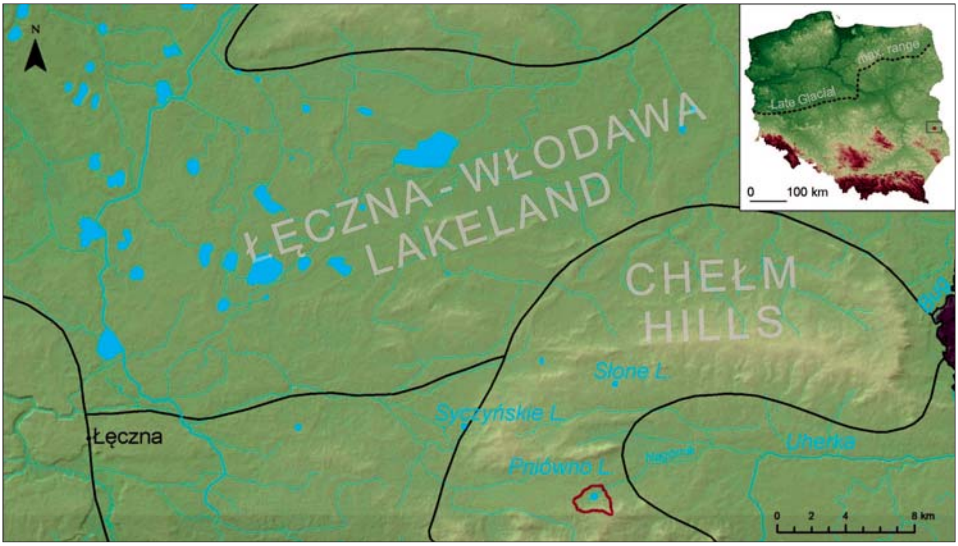

Fig. 1. Location of the study site. Red line – topographic catchment of Lake Pniówno, grey lines – regional division (after Chałubińska, Wilgat 1954)

Detailed morphometric and hydrochemical data regarding Lake Pniówno are summarized in Tab. 1 and 2. The lake’s small area and volume, as well as the catchment area predominated by agricultural land use and rural settlement, place the lake among water bodies of high eutrophication risk (Toporowska et al. 2018). In 1950, the aquatic macrovegetation was scarce, with presence of stoneworts (*Chara fragilis*, *Chara intermedia*), watermilfoil *Myriophyllum verticillatum*, and, among the nympheids, pondweed *Potamogeton natans*, *Nuphar luteum* and *Nymphaea candida*. The lake was surrounded by the belt of emergent vegetation with cattail *Typha angustifolia* and reed *Phragmites australis* (Fijałkowski 1959). In 2005–2007, only one stonewort and three submerged macrophyte species were encountered with strong predominance of hornwort *Ceratophyllum demersum* and scarce presence of water soldier *Stratiotes aloides* (Sugier et al. 2010). Extensive phytoplankton development in the lake has been observed in recent years – summer phytoplankton blooms are mentioned by Sugier et al. (2010) and blue-green algae blooms –by Toporowska et al. (2018). Nowadays, the lake is supplied by small man-made tributaries, and one large outflow (Nagórnik ditch) discharges water towards the east, to the Lepietucha River, and, subsequently, to the Uherka River.

Lake Pniówno's topographic catchment is of complex character – its elevated, southern part is built upon cretaceous rocks, whereas sands, silts and organic sediments predominate in its lower part – in the immediate lake vicinity and northern part of the catchment (Buraczyński, Wojtanowicz 1988).

Tab. 1. Selected hydromorphological features of Lake Pniówno (based on literature data after (1) Wilgat [1954], (2)Ferencz and Dawidek [2014], (3)Ferencz et al. [2017]).

Parameter	1953 AD(1)	2008–2010 AD(2)
Lake area [ha]	7.7	5.25
Max. depth [m]	3.9	2.71
Average depth [m]	1.60	1.20(3)
Volume [m^3]	121	85.55

Tab. 2. Selected hydrochemical parameters of Lake Pniówno (based on literature data after (1)Radwan et al. [1971; 1972; 1973], based on single measurement – 19.05.1967; (2)Sugier et al. [2010], based on single measurement, summer season; (3)Toporowska et al. [2018], seasonal measurements during the vegetation season – spring, summer, autumn: mean, range)

Parameter	1967 AD(1)	2006–2007 AD(2)	2008–2010(3)
pH	7.8	8.1	7.7 (7.2–8.1)
Conductivity [µS/cm]	n.d.	382	566 (529–607)
Secchi depth [m]	1.06	1.4	1.2 (1.05–1.50)
Chlorophyll – *a* [µg/l]	n.d.	14	n.d.
Total phosphorus TP [mg/l]	0.046	0.05	0.163 (0.133–0.208)
Total nitrogen TN [mg/l]	n.d.	1.9	n.d.
Ca [mg/l]	80.2	n.d.	n.d.
Trophy Status Indicator, TSI (Carlson 1977)	n.d.	59.2 (mean TSI_{SD}, TSI_{TP}, TSI_N, TSI_{chl-a})	63 (mean TSI_{SD}, TSI_{TP})

Note: n.d. – no data.

MATERIALS AND METHODS

Sediment sampling was performed during 2010 winter season. The 56-cm sediment core of olive-brown algae-carbonate gyttja was collected with a Uwitec gravity corer (6 cm inner diameter), from the central part of the basin (Pni-A, at 51°14’46,81”N, 23°20’32,56”E), at water depth of 2.65 m. Directly after sampling, the sediments were cut into 1 cm slices, packed in plastic and kept at 4°C until the laboratory work was undertaken.

AGE DETERMINATION

The sediment sequence was dated utilizing the ^{210}Pb method, in the Laboratory of Institute of Geological Sciences, Polish Academy of Science in Warsaw. For ^{210}Pb analysis, a volumetric sample (3 cm^3) of homogenized sediment was taken from each level. For all sediment samples bulk density and water content were determined. Herein, samples were dried at 105°C to constant weight, and homogenized in an agate mortar. The ^{210}Pb activity of sediments was determined indirectly by alpha-spectrometry measurement of ^{210}Po (Eα = 5.31 MeV, T1/2 = 138 days) activity in 0.1–0.9 g sub-samples (Flynn 1968). Polonium was separated from the sample using concentrated hydrochloric and nitric acids and was deposited on silver disks (Flynn 1968). For complete removal of organic matter, 30% perhydrol was used. Polonium was deposited on silver disks. The activity of ^{210}Po and ^{208}Po was measured via an alfa OCTETE PC spectrometer produced by EG&G ORTEC. In doing so, a known amount of ^{208}Po (Eα = 5.11 MeV) was added to the weighed sample as an internal yield tracer, and the constant rate of unsupported ^{210}Pb supply model (CRS) was used to calculate the sediment age (Appleby 2001). Supported ^{210}Pb was determined by measurements on old sediments (older than 150–200 years) that contain no allochthonous ^{210}Pb, assuming constant activity of authigenic ^{210}Pb along the sediment column. For samples over the extent of the dating method, age was determined by extrapolation of sedimentation rate of the lowermost samples. An age-depth function was calculated using the randomization method and was fitted by means of the LOESS procedure (Clevland, Devlin 1988).

CLADOCERA ANALYSIS

The laboratory preparation of cladoceran remains followed the procedure described by Szeroczyńska and Sarmaja-Korjonen (2007). Volumetric samples (1 cm^3 of wet sediments) were treated with 10% HCl to eliminate carbonates, and heated in 10% KOH for 15 minutes to remove organic matter. After each stage of chemical preparation, the residue was washed through a 33 μm mesh sieve with distilled water. A measured volume of 10 ml of the final residue was then stained with safranine and quantitatively subsampled for microscope slides. For each slide, a 0.1 ml of well-stirred sample was taken. Depending on frequency of remains, from 2 to 4 slides were prepared from each sample. All identifiable body parts of Cladocera were counted – shells, headshields, postabdomens, postabdominal claws and ephippia. Due to high dominance in the population of three taxa (*Bosmina longirostris, Alona rectangula* and *Chydorus sphaericus*), the number of 400 specimens was set as a minimum counting sum in order to properly include less abundant species. Additionally, to the Cladocera, plant remains were also counted (*Ceratophyllum* hairs, *Nymphaeaceae* statoblasts, *Chara* oospores). The identification of cladoceran remains and taxonomic nomenclature followed Szeroczyńska and Sarmaja-Korjonen (2007). For each species, the most numerous body part was chosen to represent the number of individuals. Total Cladocera abundance was expressed as the number of individuals per 1 cm^3 of fresh sediments. The diagram of percentage share of Cladocera species was prepared with Tilia software (Grimm 1992), and the biotic indexes: species richness (*n*), species diversity (expressed as Shannon–Weiner diversity index, *H'*), and dominance (*D*) were calculated and plotted with PAST (Hammer et al. 2001). Identification of Cladocera phases, reflecting lake-development stages, was supported via the cluster analysis method, using the CONISS algorithm (Grimm 1992). Calculation were made for square root transformed percentage data to downweigh dominants, while Edwards and Cavalli Sforza's chord distance were used as a similarity measure.

CHEMICAL ANALYSIS

Geochemical analyzes of the sediments were carried out in 1 cm thick layers with a 5-centimeter resolution, corresponding to that of the subfossil Cladocera analysis. Content of the organic matter (total organic carbon, TOC) and carbonates (TIC) were determined in approx. 2 g samples, by loss-of-ignition method, at 550°C/4 h and 950°C/6 h, respectively (Heiri et al. 2001). Terrigenous and total silica were also determined in approx. 1 g samples of ignited sediment (residue after determination of TOC) according to the methodology given by Woszczyk (2011). The biogenic silica content was calculated as the difference between the mass of total and terrigenous silica. Cluster grouping and principal component analysis of TOC, carbonates, biogenic and terigenic silica (percentage data) were used to analyze the data.

ARCHIVAL MAPS ANALYSIS

The analysis of changes in the lake-catchment settings was conducted with the application of 6 maps, listed in Tab. 3. Quantitative data was obtained by screen digitalization of calibrated map scans. These were calibrated and subjected to cartometric measurements in ArcMap 10.6, in accordance to the rules of historical GIS (Affek 2013; Kuna 2015). The areas of Lake Pniówno and other standing waters, wetlands, forests and length of watercourses were measured, and the results were presented in the form of maps (Fig. 3) and table (Tab. 3). In addition, to illustrate the development of the settlement network, built-up areas and the road layout were also vectorized, however, no quantitative analyzes were carried out. Due to development of drainage network and substantial spatial changes of the topographic watershed within the analyzed time span (Fig. 4), a rectangular test area of 14.54 km^2 with the centrally located lake topographic catchment (established based on the elevation model, regardless of the drainage network) was designated for contextual analysis. The measurement results on the map of West Galicia (*Carte von West-Gallizien*) and the Topographic Card of the Kingdom of Poland (*Topograficzna Karta Królestwa Polskiego*), due to their non-cartometric character, are only approximate and cannot be treated as quantitative data. However, while conducting GIS measurements on the oldest maps was hindered, their hydrographic content concerning analyzed area was presented in great detail.

RESULTS

Sediment age

Activity of ^{210}Pb were determined for 16 sediment samples of the Pni-A profile. The obtained values decline with depth, which indicates lack of profound sediment mixing. Activity of autogenic Pb was determined as 0.013 +/– 0.009 Bq/g (Fig. 2a), and value equal to the background level were found at a depth of 31 cm. The age-depth model indicates an increase of accumulation rate at the upper section of the core – from 23 cm upward (Fig. 2b). Due to being out of reach of the ^{210}Pb method, the age of the lowermost samples (> 40 cm) are only an estimation with considerable uncertainty.

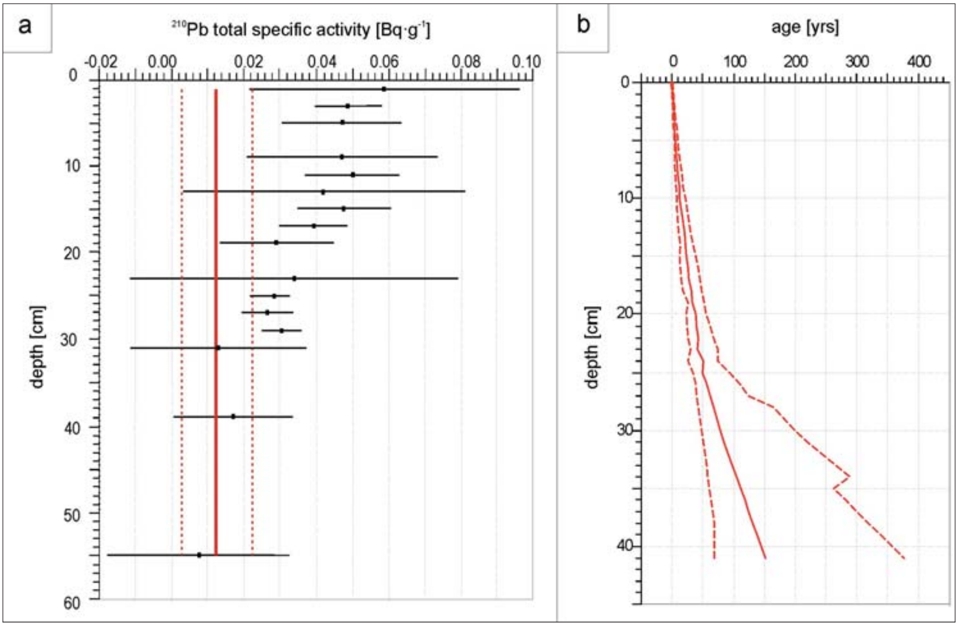

Fig. 2. a – ^{210}Pb activity in the Pni-A profile; b – age-depth model (solid line), with 95% confidence interval (dash lines)

Hydrological alterations and catchment land use

The maximum range of wetlands and forests in the analyzed period was found to have been in the first half of the 19th century (Tab. 3, Fig. 3a, b), pointing to a low degree of environmental transformation. However, even at this time, drainage ditches within the wetlands surrounding the lake are evident – a ditch and pond (most probably fishpond), which were already marked on the oldest map (beginning of the 19th century, Fig. 3a). Further drainage works covered the area of peatland north to the lake (Fig. 3b).

In the last decade of the 19th century, significant drainage and deforestation is noticeable when compared to the first half of the 19th century, mainly in the area north of the topographic catchment (Tab. 3, Fig. 3c). This came about most likely due to transformation of the wetlands and forests into agricultural land. The drying and deforestation works could have been associated with the development of the village of Wierzbica (buildings in the northwestern part of the analyzed area). Lake area declined by 1 ha as compared to the first half of the 19th century.

The map from the 1930s reveals a reduced ring of wetlands around the lake. Moreover, the surface area of the lake itself points to a lowered water level (Fig. 3d). A drainage ditch in the western part of the drainage basin, the purpose of which was to supply water to the lake, may indicate deliberate measures to

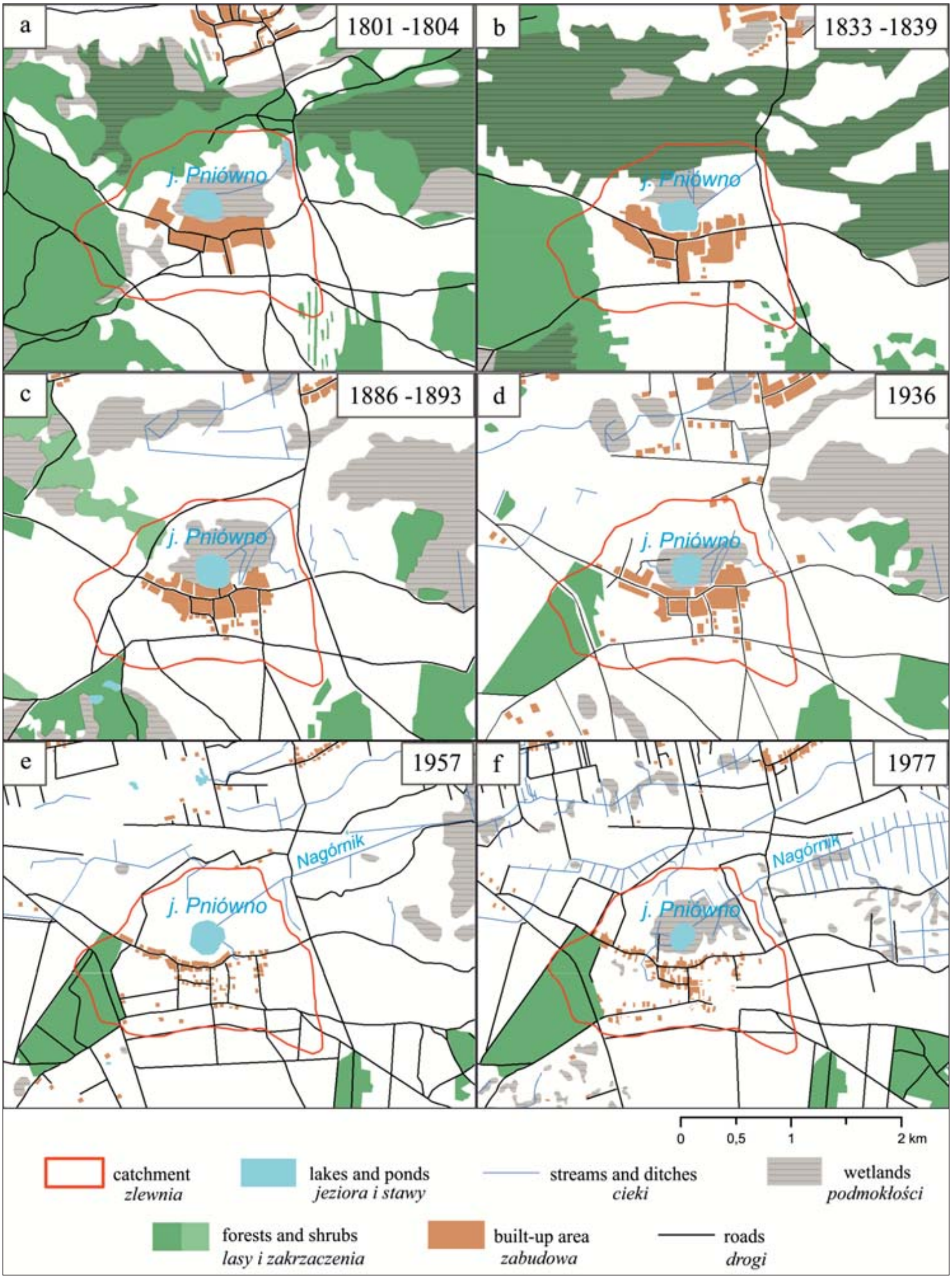

Fig. 3. Changes in land-use and hydrological network in Lake Pniówno's catchment and its surroundings (author's study based on archival maps)

Tab. 3. The results of carthometric measurements of archival maps. The percentage data were presented as referenced to the test area (14.54 km^2)

	Map	issued in (yrs)	field surveys (yrs)	Lake Pniówno	ponds	wetlands	ditches	forests
				[ha]	[ha]	[%]	[km/km^2]	[%]
1	Carte von West-Gallizien 1:172 000 *Mapa Zachodniej Galicji majora Antoniego Mayera von Heldensfelda* 1:172 000	1808	1801–1804	7.66	1.2	17.9	0.52	43.5
2	Topographic Card of the Kingdom of Poland 1:126 000 *Topograficzna Karta Królestwa Polskiego, Kwatermistrzostwo Generalne Wojska Polskiego* 1:126 000	1839–1843	1833–1839	8.85	0.0	35.8	1.04	47.6
3	Karte des Westlichen Russland 1:100 000 *Mapa Rosji Zachodniej* 1:100 000	1914	1886–1893	7.86	1.81	16.4	4.97[(1)]	13.4
4	Tactical Map of Poland 1:100 000 *Mapa Taktyczna Polski Wojskowego Instytutu Geograficznego* 1:100 000	1936–1938	1936	6.46	0.0	13.0	5.73	9.2
5	District Map of Counties 1:25 000 *Mapa Obrębowa Powiatów*1:25 000	1960	~1957	7.72	0.0	2.7[(2)]	9.23	5.8
6	Topographic Map of Poland 1:10 000 *Topograficzna mapa Polski, Główny Urząd Geodezji i Kartografii* 1:10 000	1984	~1977	4.43	0.0	4.5	21.71	8.2

[(1)]The ditch north of the catchment on the next map almost exactly overlaps with the road on further maps which raises doubts as to the correctness of its mapping and therefore was excluded from the analysis, [(2)]unreliable result (see the comments in Discussion)

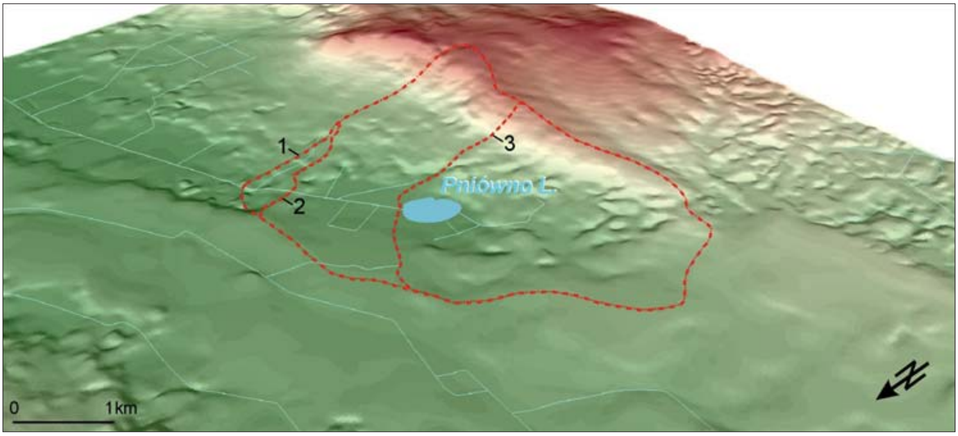

Fig. 4. Digital elevation model of Lake Pniówno catchment, dash line – changes of topographic catchment: 1 – beginning of the 19th century until the 1830s; 2 – the 1930s; 3 – since the 1950s. Stream network reflects 2010 AD (author's own study based on Topographic Map of Poland 1:10 000)

sustain water level. In addition, the reduced length of the ditch on the north-eastern side of the lake suggests that water was not discharged from the catchment, which most closely resembled its natural, topographic range (Fig. 4). Settlement, however, continued to develop, including in the lake catchment area (individual buildings in its northwestern part).

The most important change in hydrological setting, shown on *Mapa Obrębowa Powiatów* (~1959 AD), was the "opening" of the topographic catchment by construction of the outflow from the lake towards the Nagórnik ditch. Its existence was reported even earlier (1953 AD) by Wilgat (1954). This ditch provides permanent outflow from the lake to the Uherka River basin. The map also shows the increased (relative to the 1930s map) extent of the lake. What is more, the lake surface and water level are higher than shown on the further topographic map (*Topograficzna mapa Polski*). However, the total lack of wetland around the lake, which is not marked on the map, is questionable. The unreliable of the mapping regarding the extent of wetlands on *Mapa Obrębowa Powiatów* is also confirmed by other authors pointing this source as being the least reliable among the 19th-century topographic maps (Mięsiak-Wójcik 2018).

Topographic map 1:10 000 presents in great detail the state of the catchment and its intermediate vicinity in the late 1970s. Therein, the lake area and lake level were the lowest in the whole analyzed period and the drainage network was at the greatest expansion. The area of wetlands diminished by over 30% with regard to the situation presented on Tactical Map of Poland.

Subfossil Cladocera analysis

Remains of 22 Cladocera species belonging to three families (Daphniidae, Bosminidae and Chydoridae) were found in the sediments of the Pni-A core. Species richness (*n*) within subsamples was between 8 to 18. Total Cladocera abundance ranged from 6,000 to 47,000 ind./cm^3. Species diversity measured by the Shannon–Weiner index (*H'*) was from 0.71 to 1.52, whereas dominance (*D*) varied from 0.3 to 0.6. Species *Bosmina longirostris* dominated in the entire profile, with percentage from 35 to 80%. Subdominant taxa were *Chydorus sphaericus* s.l. (8 to 40%) and *Alona rectangula* (8 to 20%). Share of planktonic species differed from 35 to 80%, whereas the littoral was from 20 to 65%. Based on the identification results, two phases of Cladocera development were distinguished: CAZ-1, CAZ-2, with sub-phases (CAZ-2a, 2b).

CAZ-1 phase (44–55 cm, > 1865 AD). Only 15 cladoceran taxa were identified in this phase (Fig. 5, 6), with species richness within sub-samples ranging from 9 to 14. Of these, *Bosmina longirostris* (74–79%) was of highest abundance in all the samples, with *Alona rectangula* (9–13%) and *Chydorus sphaericus* (10–11%) as sub-dominants. In this phase, taxa associated with high trophic status dominated – besides the aforementioned, these were also represented by *Pleuroxus uncinatus*, *Oxyurella tenuicaudis* and *Leydigia acanthocercoides*. Among planktonic taxa, *Daphnia longispina* gr. was present. A characteristic feature of this phase of cladoceran development were very high total Cladocera abundance (38,800–47,200 ind./cm^3), low diversity (*H'*: 0.71–0.85) and high dominance (*D*: 0.58–0.64).

CAZ-2 phase (0–43 cm, ~1845–2010 AD). In this phase 21 taxa were present. As before, the dominant species were *Bosmina longirostris*, *Alona rectangula* and *Chydorus sphaericus*. However, during this phase, a noticeable increase in the share of macrophyte-associated littoral species, as well as species associated with sediment substrate were noted. Moreover, a marked decrease of abundance of *Bosmina longirostris* was observed. The share of species associated with high trophy of waters had not changed significantly. In this phase two sub-phases were distinguished:

Sub-phase 2a (22–43 cm, ~1845–1960 AD). This sub-phase is marked by substantial decrease of *Bosmina longirostris*, whereas *Chydorus sphaericus* reaches its maximum abundance (23–43%). A slight but steady increase in numbers of *Alona rectangula* (13–17%) was also noted. In the mid- of the sub-phase, the decline of planktonic species was compensated by increase of the littoral, plant-associated (*Graptoleberis testudinaria*, *Alona affinis*, *Pleuroxus trigonellus*, *Alonella exigua*), as well as sediment-associated species (*Pleuroxus*

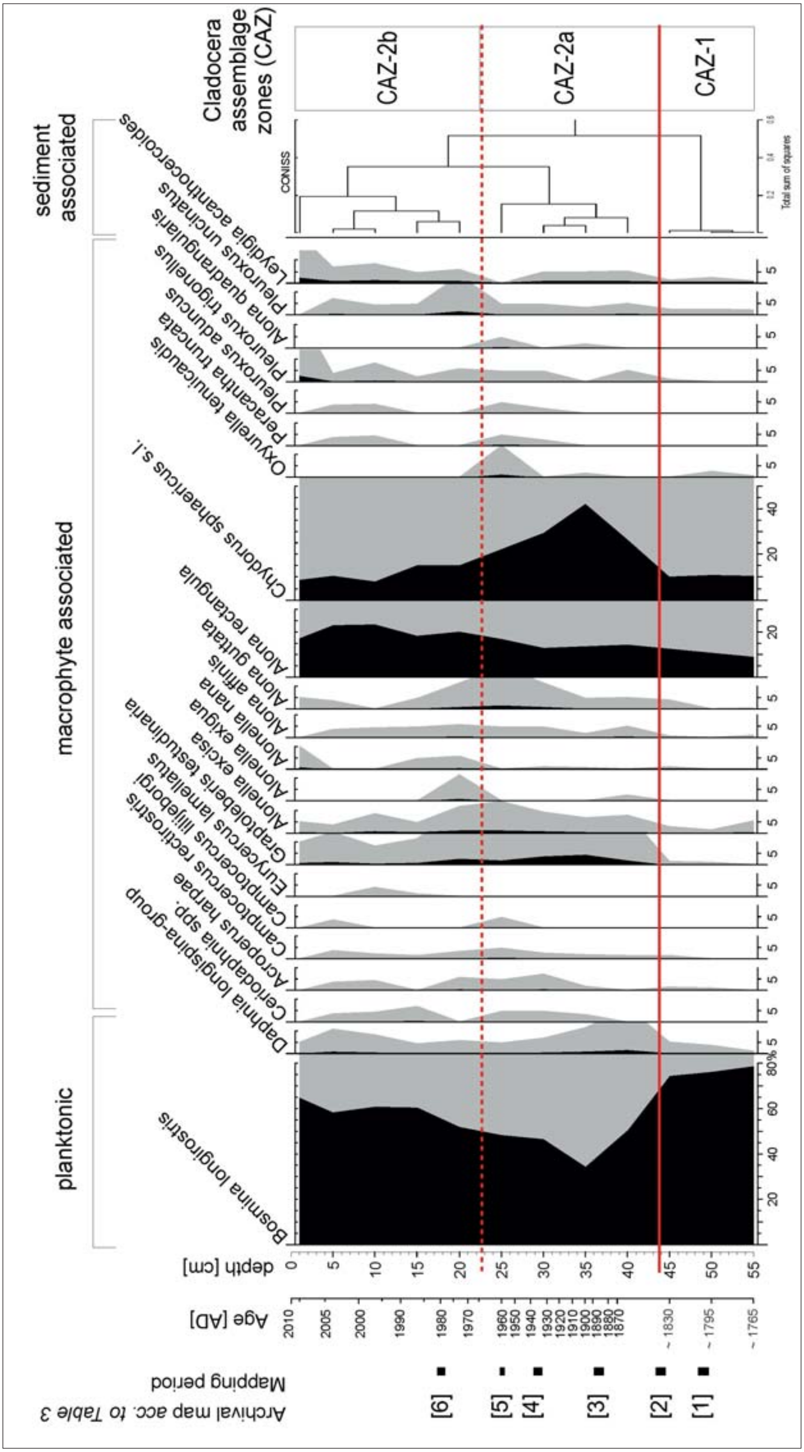

Fig. 5. Changes of subfossil Cladocera composition in the Pni-A profile (author's own study)

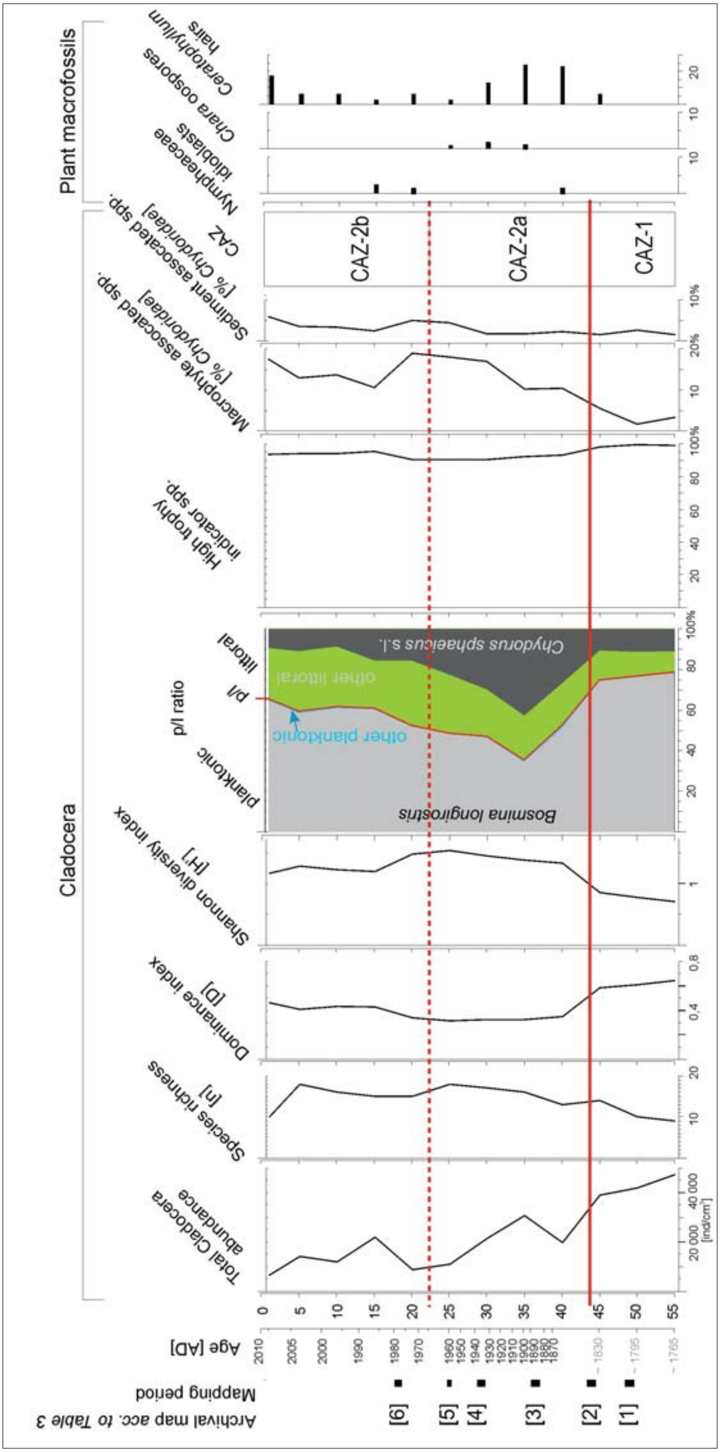

Fig. 6. Changes of Cladocera diversity and selected macrofossil remains in the Pni-A profile (author's own study)

uncinatus, *Alona quadrangularis*). Taxa *Alona quadrangularis* occurred solely during this sub-phase. The end of the sub-phase was marked by the appearance of *Alona guttata*, *Oxyurella tenuicaudis*, *Pleuroxus uncinatus* and *Camptocercus lillijeborgi*.

For the entire sub-phase, decline in total Cladocera abundance (10,800–30,600 ind./cm^3) and dominance (*D:* 0.32–0.35) was evident. At the same time, the diversity index (*H':* 1.34–1.52) and the species richness (*n:* 13–18) were the highest within the entire profile.

Sub-phase 2b (0 – 22cm, ~1967–2009 AD). In this sub-phase an increase in abundance of *Bosmina longirostris* and *Alona rectangula* was seen. At the onset of this sub-phase, the many of the species present in the earlier sub-phase declined until complete decay (*Acropeus harpae*, *Camptocercus rectirostris*, *Alonella exigua*, *Alona affinis*, *Peracantha truncata*, and *Camptocercus lillijeborgi*). In the mid part of sub-phase 2b, *Eurycercus lamellatus* makes the only appearance in the studied sediment sequence, and at the end of sub-phase, the increase of *Alonella nana*, *Pleuroxus trigonellus* and *Leydigia acanthocercoides* was notable.

In sub-phase 2b,decline in total Cladocera abundance (6,500–21,800 ind./cm^3) and species richness were indicated (*n:* 10–18), as well as an increase in dominance (*D*: 0.41–0.46) and decline in diversity (*H':* 1.16–1.48). The decline of littoral taxa (similarly to Cla-1) – mostly the plant-associated – was seen, whereas sediment-associated taxa increased, especially these adapted to high trophy and low oxygen conditions (*Leydigia acanthocercoides*).

GEOCHEMICAL ANALYSIS

Three geochemical zones were identified (Fig. 7) based on changes of total organic carbon (TOC), carbonates and two forms of silica ($SiO_{2\ biog}$, SiO_{2ter}).

GZ-1 (depth 40–55 cm, > 1865 AD). In this zone, the highest values of total organic carbon (45.5% ±0.98) and both forms of biogenic and terrigenous silica were noted (9.8% ±1.7 and 21.6% ±1.1, respectively), whereas calcium carbonate levels oscillate around 21% (21.4% ±1.2), which were the lowest values in the entire examined sediment section.

GZ-2 (depth 15–35 cm, ~1900 – ~1987 AD). Herein, values of sedimentary calcium carbonate (33.6% ±4.0) were substantially higher than in GZ-1, with increasing trend. In addition, a simultaneous decline of TOC (34.6% ±2.8), as well as terrigenous silica (9.3% ±1.8), were typical for the zone.

GZ-2a (depth 20–35 cm, ~1900 – ~1970 AD) and **GZ-2b** (depth 10–15 cm, ~1970 – 2000 AD) sub-zones were delimited base on the reverse of declining

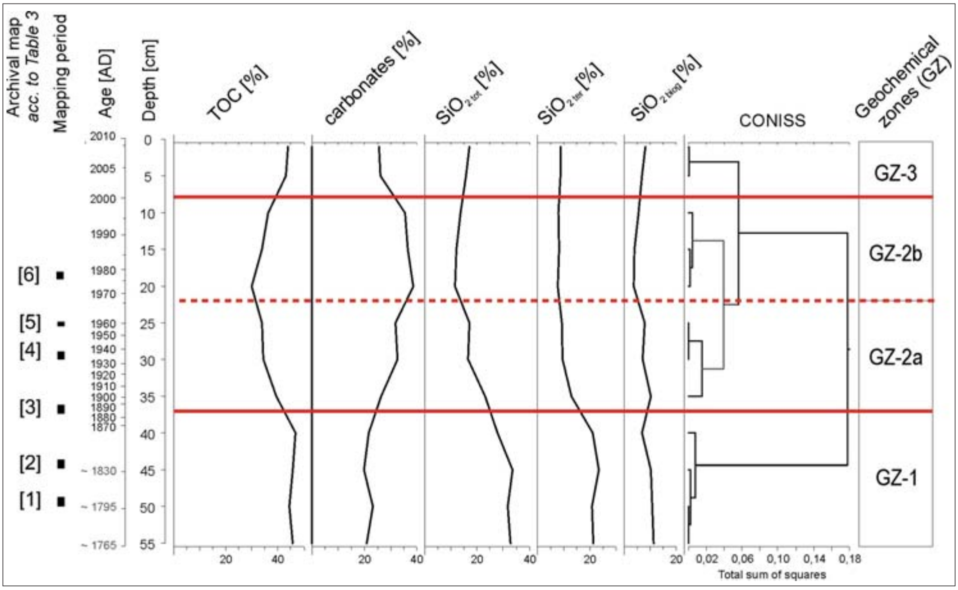

Fig. 7. Changes in the chemical composition of the Pni-A profile sediments (author's own study)

trend in TOC values (mean value for the sub-zone 32.0% ±1.9) and in biogenic and terrigenous silica. In GZ-2a, the values of biogenic silica remained similar to GZ-1 (8.3% ±1.3), whereas in GZ-2b, these declined significantly (4.4% ±0.8).

GZ 3 (depth 1–5 cm, 2010–2004 AD). This zone was delimited based on the substantial decline in calcium carbonate (28.0% ±0.3), as well as having high values of TOC (47.1% ±0.4) comparable to these in GZ-1.

DISCUSSION

Data on changes of ecological status of Łęczna-Włodawa Lakes covering periods longer than a few decades are scarce. So far only few lakes: Kleszczów (Kornijów et al. 2016), Rotcze (Kowalewski et al. 2016) and Głębokie Uścimowskie (Kowalewski et al. 2013) have been comprehensively studied by applying paleolimnological methods. Although for all these lakes the development of macrophytes were very important phenomena, the results clearly point to the considerable differences in the trajectories of their changes within the last 200 years, as well as the important role of local factors in the process, especially with regard to transformation of their catchment.

Preliminary paleolimnological data for Lake Pniówno largely extend the spatial and ecological gradient of the studied ecosystems, by providing information regarding a site that is different hydrochemically and which has remained under long and permanent anthropogenic impact. The existence of the settlement of the Pniówno village at the southern shore of the lake is visible on the Heldensfeld map from the beginning of the 19th century, but the village was first mentioned in historical sources as of 1414 AD (Wawryniuk 2010). The quantitative data about the settlement dynamic since the early 19th century (Fig. 8), together with the data regarding land-use (Fig. 3, Tab. 3) serve as the partial measure of the impact. Unfortunately, despite the long time array covered by the Pni-A sediments, due to the long history of settlement in the immediate vicinity of the lake and earlier than for most of the Łęczna-Włodawa Lakes, anthropogenic interference into hydrological settings of the catchment, the natural, pre-disturbance conditions of the lake were not covered by the presented analysis.

The high trophic status of the lake during the whole time span covered by the study is unambiguously confirmed by the very high total abundance of Cladocera, the low species diversity and, most importantly, by the strong co-dominance of three taxa associated with elevated nutrient status: *B. longirostris*, *A. rectangula* and *C. sphaericus* (Liu et al. 2014; Szeroczyńska 1998). It is worth highlighting that, despite the high target counting sum, not even a single occurrence of Cladocera taxa with preference towards low (oligo- or mesotrophic) trophic status were noted.

Interestingly, contrary to what might be expected, ecological changes of the ecosystem reflected in Cladocera phases, were not unidirectional with time and did not vary along with the increasing anthropogenic impact. The period of high trophy and low ecological status which should be understood as turbid water and phytoplankton-dominated condition of the lake (Scheffer, van Nes 2007), corresponds to the oldest of the identified phases (CAZ-1, GZ-1), when the settlement of the Pniówno village was yet the lowest (Fig. 8). By no doubt it is the agriculture and the rural sewage disposal that are major source of the nutrients in Lake Pniówno waters, therefore, one can expect that this impact should increase with farming intensity and population density, therefore, the opposite conclusions derived from paleolimnological analysis should be examined in detail. Despite the high uncertainty of age determination for this phase it can be assumed that these covers at least the period from the mid-18th to the mid-19th century. This estimation indicates that the bottommost section of the Pni-A core may partially correspond to the Little Ice Age (LIA, 1550–1800 AD). So far this cooling period has not been studied in detail in Polesie Region, whereas for the area of Poland an increase in the continentality of climate is reported. This is documented, e.g. by lowering peat accumulation rate, and the interruption of calcareous tufa deposition in the cupola spring mires (Dobrowolski et al. 2010).

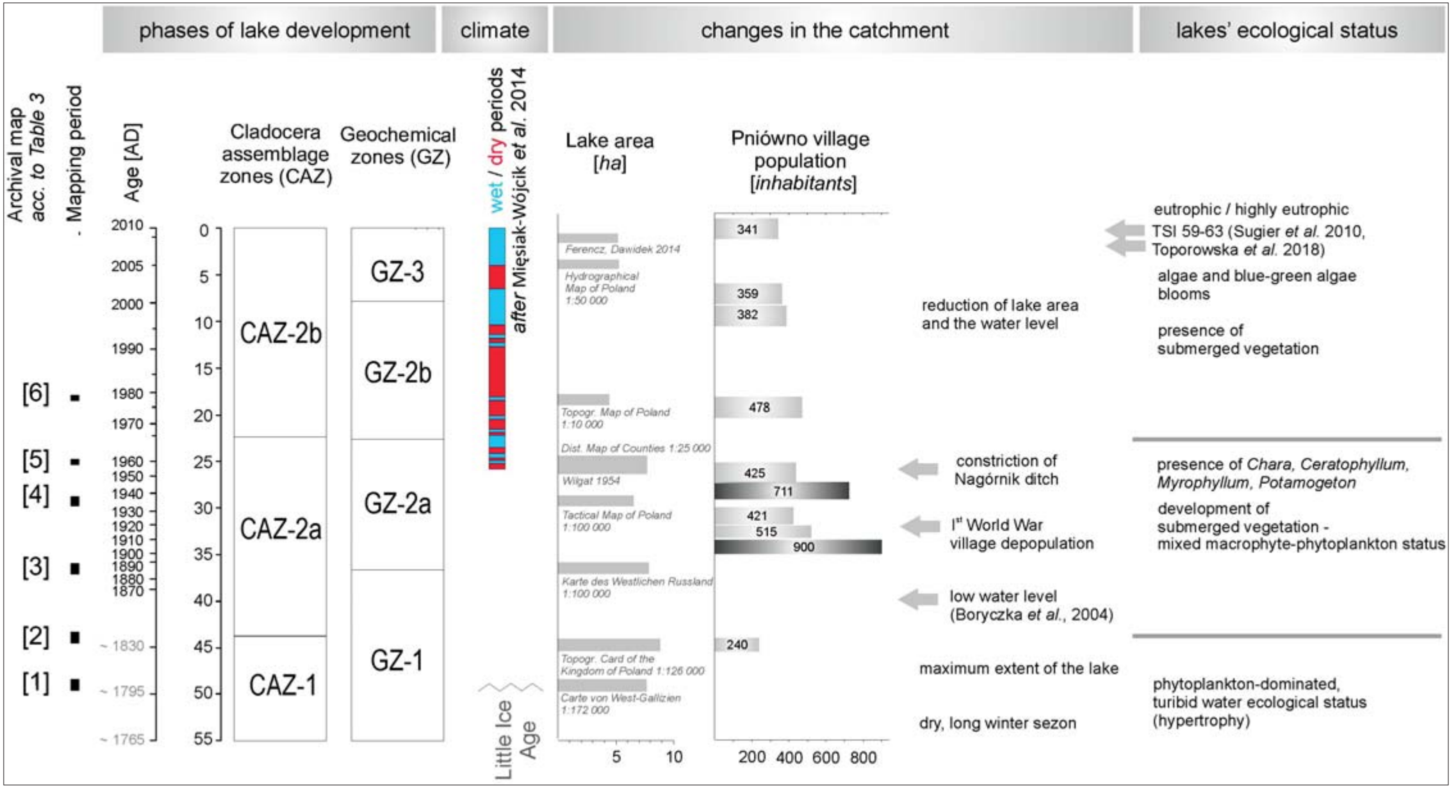

Fig. 8. Ecological status of Lake Pniówno vs. changes of environmental conditions (author's own study)

Assuming this climate-driven scenario, the extended ice-cover period and, consequently, the internal phosphorus load due to winter oxygen deficits, might have contributed to the high trophy status and turbid water state of Lake Pniówno. However, due to the temperate climate of the region, the high trophic status (hypertrophy) and absolute lack of macrophytes cannot result solely from the severity of climate. Even more plausible are additional, human-related factors, as mechanical destruction of aquatic vegetation during fishing activities (by using fishing dredge) or hemp retting practices. There are paleolimnological evidence for the cultivation of hemp in the region and using lakes for fibre processing since at least the early Middle Ages (Kulesza et al. 2011; Dobrowolski et al. 2015), until at least the end of the 19th century. Multiple examples demonstrate that this practice inevitably causes severe water quality deterioration (Grönlund et al. 1986; Kulesza et al. 2011).

Despite the increasing (since the onset of 19th century) transformation of the catchment by intensification of drainage, deforestation, agricultural land use and expanding settlement (Fig. 3), the subsequent change of lake ecological status (sub-phase CAZ-2a) brought its improvement rather than further decline. Although Cladocera are usually very reliable indicator of water level fluctuations with application of planktonic to littoral (p:l) ratio (Alhonen 1970; Korhola et al. 2000), in this study the community structure was so strongly shaped by elevated trophic status (Fig. 6), than the inference of this parameter is biased. A high share of *B. longirostris* and *C. sphaericus* hampers reconstruction of water level fluctuations, as during the blue-green algae blooms, both taxa can thrive outside of their typical environments (Gąsiorowski, Hercman 2005). Therefore, in this study, mostly data from archival maps contribute to reconstruction of this parameter. For this time, cartographic materials suggest slight lowering of the water level (Fig. 8). Although the water level information should always be interpreted with caution (Kowalewski 2012; Mięsiak-Wójcik 2018), this information is in line also with climatic data. According to literature, in the second half of the 19th century, Poland faced prolonged drought (a decrease in the amount of precipitation since 1855, including low rainfall in the winter half-year, a time particularly important for shaping lake water resources), with a minimum in 1880 AD (Boryczka et al. 2004; Michalczyk et al. 2011). Although decline of water level in shallow lakes often results in increased of wind mixing, mobilization of nutrients and worsening the water quality (Wetzel 2001), the studied case might exemplify the opposite. The water decline interplays with submerged aquatic vegetation appearance and expansion (e.g. *Ceratophyllum demersum* and Characeae), as proved directly by presence of plant macrofossils, as well as by increased abundance of macrophyte-associated Cladocera taxa. This is a clear manifestation of the improvement of ecological conditions which is confirmed by the increase of Cladocera richness and diversity. The increased carbonate deposition, as well as development of benthic cladoceran taxa (*A. quadrangularis*, *P. uncinatus*) might prove the reduced oxygen deficits (Błędzki, Rybak 2016). Moreover, the decline of terrigenous silica stands for less intense catchment erosion at that time, whereas the sustained values of its biogenic form points to the high primary production of diatom and chrysophytes (Conley, Schelske 2002).

Despite the prerequisites for lowering of the water level, among the reasons for improving the ecological status the major population movements associated with World War I (primarily the relocation of the Ukrainian population in 1915–1940 AD) should also be taken into account. As a result, the number of inhabitants of the Pniówno village decreased by half (*Apokryf Ruski*). This decline coincides with first findings of *Chara* oospores. Moreover, during the second decade of 20th century, the decline in the size of the hemp crops in Łęczna-Włodawa region is reported (Jarosz, Mędrek 2014), which also agrees well with the improvement of ecological status (Fig. 6). Given the above, the macrophyte development despite the high cultural eutrophication, might have resulted from alleviation of human activity, as well as the improvement of light conditions resulted from declined water level. The subsequent factor was found to be decisive for the development of macrophytes in Lake Rotcze in the second half of the 20th century (Kowalewski et al. 2016).

However, while the transition from a turbid, phytoplankton-dominated regime to the conditions with developed submerged vegetation (*Ceratophyllum*, *Chara*) was a profound ecological change, this should not be considered as a transition to a macrophyte-dominated stable state, but rather transition to a mix macrophyte-phytoplankton regime (Scheffer, van Nes 2007).

The entire basin of Lake Pniówno is set into chalk bedrock (Suchora 2012), and its ground water supply plays an important role. This effect is stressed by Ferencz and Dawidek (2014), who also highlight its role in shaping lake water quality. The results of comprehensive hydrochemical measurements points also to the important role of flushing time for Lake Pniówno's ecological status (Ferencz, Dawidek 2014; Toporowska et al. 2018). Therefore, the major change in the surface hydrological network which was the inclusion of Lake Pniówno in the surface drainage network via Nagórnik ditch, resulted not only in the lowering of water level, but, most probably, via shortening of the retention time, also deeply affected reaction to groundwater supply. Moreover, the Nagórnik ditch also affected the range of the catchment (Fig. 4). The decrease in the lake water level due to the construction of the Nagórnik ditch and, probably, also the decrease in the amplitude of the lake water fluctuations, coincide with the warm and dry climatic period (Michalczyk et al. 2011; Mięsiak-Wójcik et al. 2014; Fig. 8). These overall changes are reflected consistently by CAZ-2b and GZ-2b sub-phases. At that time, an increase in the sedimentation rate and a further increase in the carbonate content (from 1970 to 1990 AD, 36–39%) were noted. As in the Cladocera species composition macrophyte-associated taxa decline only slightly, but solely *Ceratophyllum* hairs and *Nymphaeaceae* idioblasts, and no *Chara* oospores were identified. Still, they are listed as present in small abundance in 2005–2007, by Sugier et al. (2010). This discrepancy may result from the low resolution of analysis, or more probably, from declining as compared to CAZ-2a *Chara* population, which is usually attributed to trophy increase (Nõges et al. 2003). Moreover, the increase of taxa regarded as high trophy indicators – *B. longiostris*, *A. rectagula*, *L. acanthocercoides* (Szeroczyńska 1998) with the overall decline of diversity, point rather to the higher trophy and turbidity increase hypothesis.

Based on modern hydrochemical studies, Ferencz et al. (2017) attribute the poor quality and highly eutrophic status of Lake Pniówno water to slow water circulation in their catchment. It the context of the presented data it should be highlighted that before the 1970s (early 19th–mid 20th century, before the construction of the Nagórnik ditch), the rate of the water exchange was even lower than nowadays, yet it did not determine its poor ecological status at that time. This supports the conclusion on the important role of other, interplaying factors in shaping the ecological status of this ecosystem.

CONCLUSIONS

Although the data is of a preliminary character, based on the presented analysis, the following facts regarding Lake Pniówno are indisputably confirmed:

– the lake has had high trophic status throughout the entire period of analysis (at least the last ~200 years);

– phytoplankton dominated, turbid water status of the lake in the CAZ-1 phase, when anthropogenic pressure in the catchment area and its surroundings (deforestation, drainage, settlement) was probably the least severe (judging from the lowest number of inhabitants). This might point to (1) the important role of hydroclimatic factors and limnological conditions in shaping the quality of this shallow lake or (2) other, not fully confirmed so far, anthropogenic activities harming the lake;

– improvement of the water quality and development of submerged vegetation was indicated to have occurred during the end of the 19th, till the first half of the 20th century and its further (since the beginning of the 21st century) deterioration in water quality has been coming about.

The more detailed understanding of the mechanisms and dynamics of changes in the ecological status of this lake requires further, high resolution and multi-proxy research. To determine the lake's reference condition, a longer sediment sequence should be analyzed. However, regarding the scarcity of observational data on its water quality parameters and biocenosis, this study may serve as a framework for further investigation plans and for lake management.

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