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A shallow lake in an agricultural landscape – water quality, nutrient loads, future management

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Abstract: Qualitative analyses of nitrogen and phosphorus loads reaching the lake ecosystem provide a basis for pollution control, which is of paramount importance in shallow lakes due to the rapid turn-over of matter and energy. The studies of both external and internal loading were conducted in Lake Łeknenskie, a very shallow, through-flow lake situated in Western Poland. Strong eutrophication is manifested in rich rush vegetation and a lack of submerged macrophytes as well as nitrogen and phosphorus concentrations (max 13.04 mg N dm^{-3} and 0.32 mg P dm^{-3}, respectively). Constant domination of cyanobacteria in the phytoplankton community was noted in almost all seasons with a 98% share in summer, resulting in 20 cm water transparency and 223 µg dm^{-3} of chlorophyll-*a*. The zooplankton community was dominated by rotifers. The main source of nutrients was the River Nielba. Spatial external nutrient loading was 1.93 g P m^{-2} yr^{-1} and 77.55 g N m^{-2} yr^{-1}. An even higher load of phosphorus was released from the bottom sediments, 2.18 g P m^{-2} yr^{-1}. A comprehensive action plan is required, aiming at the reduction of both external and internal nutrient loading. A series of solutions regarding local environmental conditions should be applied in the lake catchment, including biogeochemical barriers, denitrification walls, artificial retention basins or wetlands, but most of all – improvement in the functioning of the wastewater treatment plant. Restoration is possible, however, protection measures reducing external loading should be undertaken prior to phosphorus inactivation in the water column and in the bottom sediments, supported by biological methods e.g. biomanipulation.

Key words: shallow lake, nitrogen and phosphorus loading, phytoplankton, zooplankton

Introduction

Eutrophication of lakes is a natural process which can be accelerated by human activity. It contributes to poor water quality, especially in shallow polymictic lakes. Such lakes are very abundant in many regions and their ecology differs from stratified lakes in many ways (Dokulil and Teubner 2003; Scheffer 1998; Moss et al. 2013), mainly due to a rapid turn-over of matter and energy and the lack of mechanisms permanently depositing nutrients in bottom sediments. The sediments remaining in permanent contact with warm, circulating, shallow waters (analoque of epilimnion in deep lakes) remain in a tight coupling with the water column, resulting in strong seasonal and inter-annual variability in nutrient availability and phytoplankton phenology (Burger et al. 2008). Deteriorated water quality has both environmental and economic implications, i.e. nuisance/toxic blooms hampering commercial and recreational fisheries, ecotourism as well as human-health related costs (Steinman et al. 2009). The reduction of external nutrient loading, focused especially on point sources in the catchment, aiming at the mitigation of phytoplankton blooms, does not always result in recovery from eutrophication, and expected results may be delayed due to severe internal loads (Søndergaard et al. 2001). In shallow lakes in particular, the exchange of nutrients in the sediment-water interphase plays a crucial role as a source of nitrogen (N) and phosphorus (P) for primary production (Forsberg 1989).

In the last decades of the 20th century numerous restoration projects were introduced, and although nutrient loading was greatly reduced, they did not often lead to the recovery of a clear water state (Scheffer 1998). Meanwhile, the Water Framework Directive (WFD) requires the achievement of good ecological

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status in all lakes over 50 hectares (EC 2000). Hence, a great deal of effort is expended on the evaluation of multiple new methods of lake restoration, both technical and biological ones. Recent results indicate that the simultaneous use of a variety of methods of restoration may be especially effective since they prevent feedback mechanisms (Gołdyn et al. 2014).

Prior to in-lake treatment, or even a proposal of restoration measures, studies on the sources and fluxes of N and P loads should be conducted because of their paramount importance in the control and management of eutrophication issues. Qualitative analyses of N and P loads provide a basis for pollution control in lakes (Wang et al. 2017). The assessment of the maximum nutrient loads that an ecosystem can absorb is important, both in avoiding and reducing phytoplankton blooms (Janssen et al. 2017).

Lake Łeknenskie (Western Poland) is a good example of a shallow, strongly eutrophicated lake which has lost its value for recreational use due to a significant inflow of nutrients from an agricultural catchment area. Located in the vicinity of the county town of Wągrowiec, its recreational function is very important for leisure fishing as well as hiking and biking. The aim of the study was to determine the functioning of this waterbody under strong nutrient loading from both the catchment area and bottom sediments. In addition, on the basis of external and internal load assessment, we have proposed solutions for the lake to return to the good ecological status required by the WFD.

Study area

Lake Łeknenskie is a very shallow (max depth 2.8 m, mean depth 1.6 m), through-flow lake, situated in a rural area of the Wielkopolska Region in Western Poland (52°50'08"N; 17°17'06"E) with a surface area of 57.5 ha (Choiński 2006). This waterbody is fed mainly by the River Nielba and also by a few small drainage ditches. The outflow is located in the southern part of the lake, linking it to the other eutrophic lakes Bracholin, Rgielsko and Łęgowo (Szeszycki 2000).

Its bad ecological state (according to EC 2000) and strong eutrophication are manifested in rich rush vegetation, mainly of *Typhetum angustifoliae* and *Phragmitetum communis* and an almost complete lack of submerged vegetation. 13 water plant associations were stated in 1996, among which 10 belonged to the rush communities, one to submerged vegetation (*Potametum pectinati*), one to nymphaeids (*Nupharo-Nymphaeetum albae*) and one to pleustophytes (*Lemno-Spirodeletum polyrrhizae*) (Messyasz and Nagengast 2000). Currently, 23% of the total area of the lake is covered with hydromacrophytes, forming only 7 plant communities. There is a lack of floating leaves plants and only one small patch of elodeids is present (a few square metres of *Potametum pectinati* in shallow water near the beach).

A high trophic state with a simultaneous degradation of water quality (cyanobacteria blooms, fish deaths) significantly influenced the type of fish populations in the lake. Catches in the 90s of the 20th century showed an increase of the population of tench, perch, roach and crucian carp in the lake (Szeszycki 2000). However, these populations have decreased in number with increasing pollution and the lack of submerged vegetation.

Łeknenskie Lake is characterized by a large agricultural catchment area (87 km^2, Schindler ratio 63.2) and quite well organized water and wastewater management. The main tributary of the lake, the River Nielba, collects pollution from point sources of several villages and from spatial sources, mainly agricultural areas. The main point source of contamination is wastewater outflow from the secondary wastewater treatment plant (WWTP) in Damasławek (population equivalent in 2008 was 3705). Unfortunately, it only removes the organic matter and discharges wastewater with a high content of nutrients to the receiver, which is a ditch flowing to River Nielba.

Methods

Water from the lake was sampled six times in all seasons between August 2011 and April 2012 at one sampling station in the deepest place of the pelagial zone, at 2.8 m (Fig. 1). Water samples were collected in depth

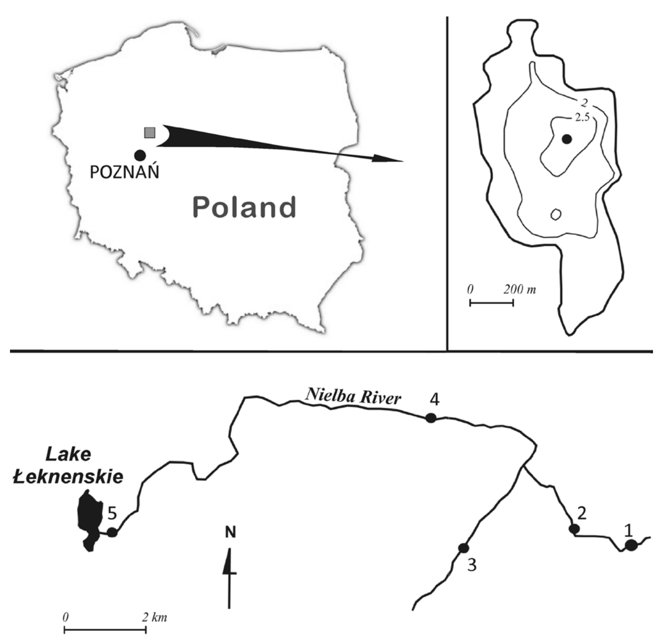

Fig. 1. Location of sampling stations (dots) on Łeknenskie Lake and the River Nielba

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profile every metre from the surface to a depth of 2 m for the analyses of ammonium nitrogen, nitrite, nitrate, organic and total nitrogen (TN), soluble reactive phosphorus (SRP), total phosphorus (TP) and chlorophyll-*a* concentrations. Water temperature, pH, conductivity and oxygen content were measured directly in the lake, using a YSI 610-DM-meter. Water transparency was measured using a Secchi disc. Physico-chemical analyses were made according to Polish standards (Elbanowska et al. 1999). Chlorophyll-*a* was assessed with the Lorenzen method. Trophic conditions were estimated using the criteria proposed by Carlson (1977).

Samples for phyto- and zooplankton analyses (species composition and quantitative analyses) were taken in depth profile at the same station. The identification of phytoplankton species was carried out based on current taxonomic criteria. Algae were counted using a chamber of 0.4 mm in height. Cells were the main counting units. For filamentous cyanobacteria and green algae the unit length of 100 μm was regarded as one individual. The biomass of algae was determined using the volumetric method by comparing algae to geometrical figures (Rott 1981).

Zooplankton samples were concentrated using a plankton net (40 μm mesh size) and preserved in 75% ethanol. *Cladocera*, *Copepoda* and *Rotifera* were counted in a 1 mL Sedwick-Rafter chamber under a Zeiss Axioplan light microscope. Taxonomic identification was performed using keys by Rybak and Błędzki (2010), and Radwan et al. (2004). TSI indices for Rotifera were calculated according to Ejsmont-Karabin (2012).

Samples of bottom sediments were taken at the same station in the pelagial zone of the lake. The upper layer of bottom sediments (10 cm thick) was sampled for analysis of organic matter content (Myślińska 2001) as well as TP content. Phosphorus was fractionated in collected sediment samples by the modified protocol proposed by Psenner et al. (1988). The fractions were: loosely bound phosphorus (NH_4Cl-P), phosphorus bound with iron (BD-P), phosphorus bound with aluminum and organic matter (NaOH-P-Al and NaOH-NRP, respectively), phosphorus bound with calcium (HCl-P) and the residue (Res-P), which was the difference between total P concentration and the sum of the first four fractions.

Quantitative analyses of internal P loading rates from bottom sediments were done using *ex situ* experiments with intact cores of bottom sediments sampled by a modified Kajak tube sampler. The cores were sampled into transparent tubes in three replicates and then transported to the laboratory. They were incubated in specific thermal and oxide conditions, similar to the natural conditions within the lake during the sampling. On the basis of experimental results, P release (mg P m^{-2} d^{-1}) was calculated. Annual areal P loading was the sum of values calculated for every season.

During the same period, water from the main tributary of the lake, i.e. the River Nielba, was sampled just before its inlet to the lake. The same physico-chemical parameters as in the lake water were analysed, and flow rate was measured directly in the field with a hydrometric current meter. The nitrogen and phosphorus loads flowing into the lake were calculated as their concentration (kg m^{-3}) multiplied by discharge (m^3 d^{-1}) at the sampling station. The results were compared with the Vollenweider criteria (Vollenweider 1976).

Additionally, a thorough research was carried out in spring 2013, the objective of which was to determine the load of pollutants flowing to the lake with the River Nielba. It included 3 sampling stations located in the river (stations 3, 4, 5) and two in the drainage ditch flowing into the river (stations 1 and 2, above and below the wastewater input, respectively, Fig. 1), which is the receiver of treated wastewater from WWTP in Damasławek. Nutrient content in the water samples was analysed (N and P) and water flow was measured directly in the field in the stream. On the basis of the data, nitrogen and phosphorus loads which were flowing with the waters of the River Nielba to Lake Łeknenskie were calculated.

Results

A. Lake Łeknenskie

Lake water chemistry

The temperature in the depth profile of the water column was almost equal both during summer and under ice cover in winter. Oxygenation of water was high during all the study periods and exceeded 100% with the exception of early autumn. Highest pH was noted in summer, reaching 8.5 (Table 1). Conductivity values were more diverse, from 606 μS cm^{-1} in winter to 1332 μS cm^{-1} in early spring. They increased in depth profile in winter, while in other seasons were aligned. Transparency was very low, within the range of 0.2 m in September to 0.95 m in February. It was negatively correlated with chlorophyll-*a* values, reaching 223 μg dm^{-3} in summer and only 2.9 μg dm^{-3} in winter.

Lake water was characterized by a high concentration of nutrients. In the case of mineral nitrogen, ammonium N had the largest share in summer (up to 100%), while nitrate N in winter (90%). The concentrations of ammonium N ranged from 0.83 mg N-NH_4 dm^{-3} (November) to 2.14 mg N-NH_4 dm^{-3} (February). Nitrates were stated only in winter, up to 6.5 mg N-NO_3 dm^{-3} (Fig. 2A). The values of organic nitrogen changed between the seasons from 1.51 mg N dm^{-3}in

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Table 1. Minimum, maximum, mean value and standard deviation (SD) of parameters analysed in the water column of Łeknenskie Lake

Parameter/Unit	Minimum	Maximum	Mean	SD
Temperature [°C]	0.7	17.4	9.9	6.7
pH	7.67–8.51		–	–
Conductivity [µS cm^{-1}]	606	1332	901	219
Oxygen concentration [mg O_2 dm^{-3}]	4.4	29.7	13.3	6.5
Oxygenation [%]	79	215	123	38
Ammonium N [mg N dm^{-3}]	0.83	2.14	1.07	0.39
Nitrite N [mg N dm^{-3}]	0	0.016	0.007	0.007
Nitrate N [mg N dm^{-3}]	0	6.54	1.68	2.87
Mineral [mg N dm^{-3}]	0.88	7.89	2.76	3.09
Organic N [mg N dm^{-3}]	1.51	4.66	3.04	1.02
TN [mg N dm^{-3}]	2.97	11.64	5.79	3.02
SRP [mg P dm^{-3}]	0.008	0.16	0.09	0.05
TP [mg P dm^{-3}]	0.055	0.32	0.17	0.10
Chlorophyll-*a* [µg dm^{-3}]	2.9	223.2	55.7	80.96
Transparency (Secchi disc depth) [m]	0.20	0.95	0.61	0.32

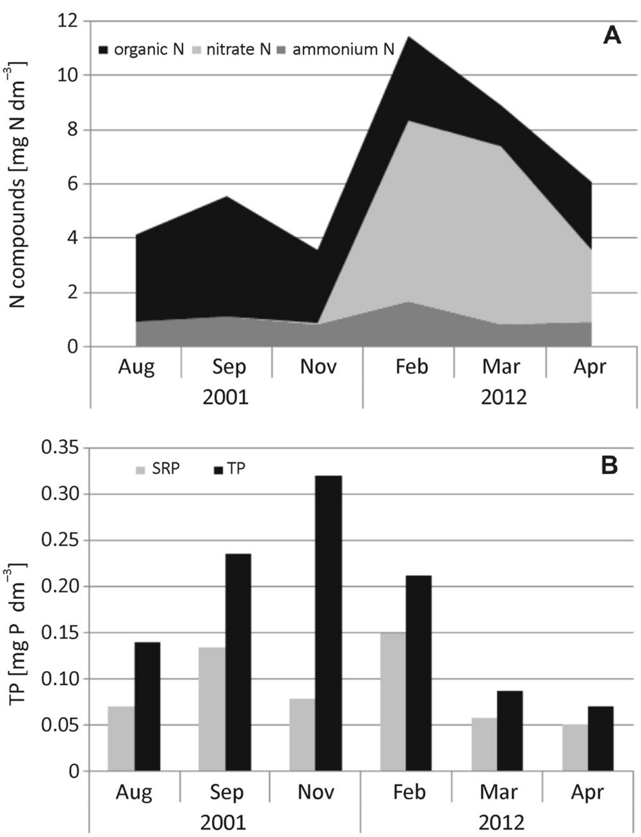

Fig. 2. Seasonal variability of nitrogen and phosphorus compounds in the waters of Lake Łeknenskie

winter, up to 4.66 mg N dm^{-3} in summer. The share of organic forms in the TN was much higher in summer than in winter. Concentrations of P were also high. TP increased from summer (0.14 mg P dm^{-3}) till autumn (0.32 mg P dm^{-3}), and decreased again in winter to a minimum in spring (0.07 mg P dm^{-3}). SRP concentrations were less diverse, varying from 0.05 to 0.15 mg P dm^{-3} (Fig. 2B, Table 1).

Trophic state index (TSI) according to Carlson (1977) indicated that Lake Łeknenskie was hypereutrophic (mean TSI 79.6). This was indicated by all indices, especially the index based on the concentration of chlorophyll-*a* (TSI_{Chl} 83.4).

Phytoplankton and zooplankton community structure

Clear cyanobacteria dominance during the summer and autumn (90–97% of the total biomass) with a lowered share in the winter (7%) and spring (40%) was noted in the phytoplankton structure. The share of other groups of algae in phytoplankton biomass was small, and cryptophytes were the most numerous (from 0.8% in August 2011 to 62% in March 2012), which was related to the numerous presence of *Cryptomonas ovata* Ehr. and *Cryptomonas curvata* Ehr. (Table 2). In summer and autumn water blooms were created by one species of cyanobacterium *Planktothrix agardhii* (Gom.) Anagn. et Kom. associated with two other cyanobacteria species *Limnothrix redekei* (Goor) Meffert and *Aphanizomenon flos-aquae* Ralfs ex Bor. and Flah. Only a few green algae, such as *Phacotus lenticularis* (Ehr.) Deising, *Monoraphidium komarkovae* Nyg., *M. contortum* (Thuret) Kom.-Legn. and *Oocystis lacustris* Chodat participated clearly in the total biomass of phytoplankton. *Phacotus lenticularis*, which accompanies cyanobacteria during their massive growth in the lake is particularly worthy of note, and its presence in Lake Łeknenskie confirms a high concentration of nutrients.

Among diatoms *Cocconeis placentula* Ehr., *Cyclotella radiosa* (Grun.) Lemm., *Ulnaria delicatissima* var. *angustissima* (Grun.) Aboal and Silva, *Ulnaria ulna* (Nitzsch) Comp. and *Fragilaria crotonensis* Kitt. were the most numerous. A clear increase in the proportion of diatoms in the phytoplankton community was observed in winter when the dominant diatom *Cyclotella radiosa* reached 17% of the total biomass. The sharp increase in

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Table 2. Comparison of the biological parameters and indices in the water of Lake Łeknenskie. TSI_{ROT} – trophy state indices based on total number of Rotifera (TOT) and share of bacterivorous rotifers (BAC) (Ejsmont-Karabin 2012)

Biological parameter/Unit	2011			2012		
	Aug	Sep	Nov	Feb	Mar	Apr
Total phytoplankton biomass [mg dm^{-3}]	87.28	158.41	41.72	2.49	3.24	10.11
Cyanobacterial biomass [mg dm^{-3}]	84.97	153.1	37.93	0.18	0.62	3.43
Cryptophytes' biomass [mg dm^{-3}]	0.67	2.15	0.66	0.60	1.96	4.40
Diatoms' biomass [mg dm^{-3}]	0.47	1.50	0.16	1.07	0.20	1.21
Planktothix agardhii share in the total biomass [%]	91	88	44	12	14	16
Limnothrix redekei share in the total biomass [%]	2	3	27	17	15	15
Aphanizomenon flos-aquae share in the total biomass [%]	5	5	15	1	1	3
Shannon-Wiener index for the phytoplankton	0.57	0.82	1.89	3.78	3.59	3.40
$TSI_{ROT-TOT}$	–	61.3	51.1	50.5	51.9	55.4
$TSI_{ROT-BAC}$	–	59.4	61.5	59.2	60.4	60.9

the number of phytoplankton cells in March and April 2012 was connected with cryptophytes *Rhodomonas lacustris* (Skuja) Javor. (34% of biomass), *Cryptomonas obovata* Czos. (23%) and the cyanobacterium *Planktothrix agardhii* (16%).

Zooplankton were dominated by rotifers, which reached their highest numbers in September 2011 (2500 ind. dm^{-3}). During the whole study the dominating species were *Keratella cochlearis* f. *macracantha*, *K. cochlearis* var. *tecta* and *Polyarthra* sp. The high total rotifer numbers as well as dominants are responsible for the high values of TSI indices for Rotifera (Table 2). A TSI between of 55 and 65 indicates eutrophy. Cladocera were also relatively abundant (up to 100 ind. dm^{-3}), however, these were dominated by small species, *Bosmina longirostris* and *Chydorus sphaericus*. Daphnids such as *Daphnia cucullata* and *D. hyalina* were very rare.

Bottom sediment characteristics

Concentration of TP in the bottom sediments usually exceeded 1 mg P g^{-1} d.w., decreasing only in spring (Table 3). It was dominated by two fractions, i.e. Res-P and HCl-P. The content of organic matter in sediments varied from 14.1 to 17.1%, with the highest values in winter. P release from the bottom sediments into the water column prevailed over its retention in sediments in all seasons. The highest internal P loading was noted in summer, decreasing in autumn and winter, and yet increasing again in spring. The internal P load during summer reached 980 kg and 1,853.5 kg during one year (Table 3).

B. River Nielba upstream Lake Łeknenskie

River water chemistry

The river waters flowing into the lake were characterized by high conductivity, good oxygen conditions and low chlorophyll-*a* content (Table 4). Nitrogen was present mainly in mineral form. Ammonium N prevailed in summer and autumn, while nitrate N in winter and spring. TN concentrations were very high throughout the analysed period, exceeding 5 mg N dm^{-3}. The highest concentrations of TP were stated in winter (1.25 mg P dm^{-3}), while the lowest in spring (0.2 mg P dm^{-3}).

A comparison of the values of water quality variables of the lake and its main tributary shows that the River Nielba was characterized by higher conductivity, concentration of mineral forms of N, SRP and TP and a lower concentration of organic nitrogen and chlorophyll-*a*.

External loading

Nitrogen loads supplying the lake with river waters were significantly higher than phosphorus. Maximum TN loads, up to 534 kg N d^{-1} reached the lake during winter and early spring, while in the case of TP, in the winter season (up to 14.8 kg P d^{-1}). Annual lake external P loading was 1,929.5 mg P m^{-2} and N loading 77,546.3 mg N m^{-2}. The permissible nitrogen load for the lake according to the Vollenweider criteria (1976) was 478 mg N m^{-2} yr^{-1} and 31.9 mg P m^{-2} yr^{-1}, while the critical load was 956.6 mg N m^{-2} yr^{-1} and 63.8 mg P m^{-2}

Table 3. Seasonal changes of sediment characteristics, phosphorus release and internal loading from bottom sediments of Lake Łeknenskie

Season	TP	Organic matter	P release	P loading
	mg P g^{-1} d.w.	%	mgP m^{-2} d^{-1}	kg P season^{-1}
Summer	1.19	14.1	12.6	980.0
Autumn	1.41	14.7	3.0	232.6
Winter	1.44	17.1	2.2	170.6
Spring	0.69	15.4	6.0	470.3
Mean value	1.18	15.3	5.96	463.4 (1,853.5 kg P yr^{-1})

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Table 4. Minimum, maximum, mean value and standard deviation (SD) of parameters analysed in the River Nielba

Parameter / Unit	Minimum	Maximum	Mean	SD
Temperature [°C]	0.1	17.2	7.7	7.3
pH	7.46–8.51		–	–
Conductivity [µS cm^{-1}]	647	1380	976	269
Oxygen concentration [mg O_2 dm^{-3}]	9.78	15.43	13.34	2.02
Oxygenation [%]	89.5	155	112.5	25.2
Ammonium N [mg N dm^{-3}]	0.77	2.88	1.48	0.89
Nitrite N [mg N dm^{-3}]	0	0.018	0.009	0.007
Nitrate N [mg N dm^{-3}]	0	12.02	4.83	4.49
Mineral [mg N dm^{-3}]	0.87	12.79	6.32	4.38
Organic N [mg N dm^{-3}]	0.61	4.21	1.99	1.40
TN [mg N dm^{-3}]	5.08	13.44	8.31	3.29
SRP [mg P dm^{-3}]	0.06	1.09	0.33	0.39
TP [mg P dm^{-3}]	0.075	1.25	0.42	0.42
Chlorophyll-*a* [µg dm^{-3}]	1.28	8.46	4.13	2.66

yr^{-1}, respectively. It is thus apparent that the permissible load has been exceeded 60 times in the case of TN and 162 times in the case of TP. Critical loads were exceeded by 30 and 81 times, respectively.

The detailed study on the loads of nutrients flowing along river in spring 2013 showed that mineral forms of nitrogen markedly increased in the lower course (station 4 and 5), while in the upper course as well as in the tributary (station 1–3), which carries the treated wastewater from WWTP Damasławek, they were relatively low (Fig. 3). Loads of P compounds were more dependent on the impact of treated wastewater than in the case of nitrogen. Between stations 1 and 2 they increased almost 4-fold (SRP) and 3.5-fold (TP). The lowest loads in the water of the River Nielba were stated in its upper course (station 3), which increased markedly below the ditch carrying the wastewater from Damasławek (station 4) and strongly in the lower course, flowing through the agricultural area, especially in relation to the TP (Fig. 3).

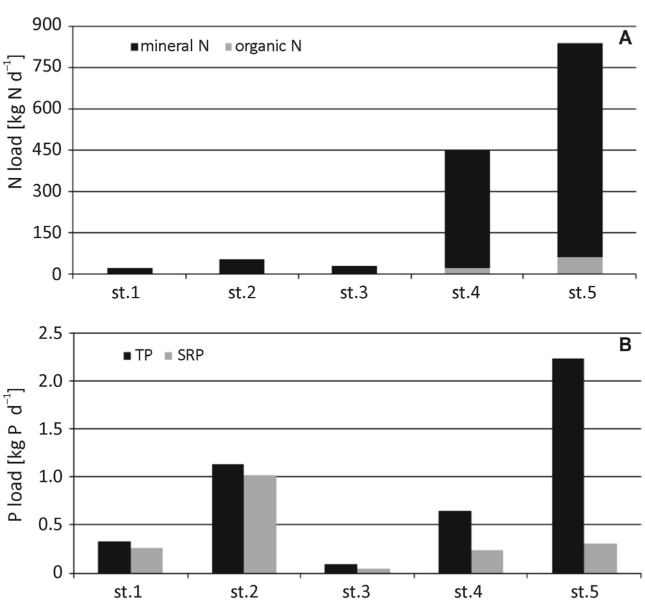

Fig. 3. Changes of nitrogen and phosphorus loads at sampling stations of the River Nielba

Discussion

Lake water quality

A high trophic level of Lake Łeknenskie was manifested in both physico-chemical and biological variables. Comparison with threshold values given by OECD (1982) for water transparency (both mean and minimal), chlorophyll-*a* concentrations (mean and maximal) and mean TP indicated characteristic values for the hypereutrophic status of the Lake Łekneńskie.

The intensive growth of phytoplankton with strong domination of cyanobacteria and high concentration of chlorophyll-*a* up to 200 µg dm^{-3} indicated – according to the guidelines of the WFD (EC 2000) – bad ecological status of the lake. Intensive growth of phytoplankton also caused significant oversaturation of the water with oxygen and an increase in pH values. It accelerated the mineralization of organic matter in bottom sediments due to the free circulation of the whole water column in such a shallow lake and favoured the P release from sediments which promoted the development of cyanobacteria (Kowalczewska-Madura et al. 2011; Beaulieu et al. 2013).

The presence of long-term and very intense phytoplankton blooms was the main problem of water quality in Lake Łeknenskie. The intensity of cyanobacterial blooms, including *Planktothrix agardhii* (summer and autumn) and *Limnothrix redekei* (spring), was favoured by a high concentration of nutrients, both N and P. Among the other stated species of cyanobacteria accompanying the dominants were *Cuspidothrix issatschenkoi* (Us.) Raj., Kom., Will., Hrouz., Kast., Hoff. and Siv. and an invasive tropical species *Raph-*

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idiopsis raciborskii (Woloszynska) Aguilera, Berrendero Gómez, Kastovsky, Echenique & Salerno. Each of these species may form a bloom and is a potential toxin producer (Ibelings and Chorus 2007; Kokociński et al. 2013). Their presence in the structure of the phytoplankton communities and the formation of a strong water bloom clearly indicated hypereutrophy. The ability to fix N_2 by species from the genus *Aphanizomenon* and *Raphidiopsis*, and buoyancy regulation in the cells in all cyanobacteria species allowed them to compete effectively with other groups of algae (Stefaniak et al. 2005; Paerl and Otten 2016).

An increase in the amount of cyanobacteria caused a decrease in the water transparency, and because this group of algae is resistant to such light conditions in the water, their numbers were able continue to increase, reducing the amount of light for eukaryotic algae. According to Reynolds et al. (2002) *Planktothrix agardhii* and *Limnothrix redekei* owe their development success to their great adaptability to isolate the light and to regulate their position in the water column. As representatives of the phytoplankton functional group S_1, these species dominate in waters with frequent turbulence, at low light exposure, and are often accompanied by *Aphanizomenon* sp. Such an arrangement of algal species in Lake Łekneńskie confirmed the strong polymictic, hypereutrophic nature of this water body and due to phytoplankton biomass it can be classified into the bad ecological status (Napiórkowska-Krzebietke and Dunalska 2015). The largest number of *Planktothrix agardhii* was associated with low average concentrations of orthophosphates and extremely high values of ammonium N. Such prevailing physico-chemical conditions have accompanied the bloom of cyanobacterium *P. agardhii* in other shallow lakes of the region (Grylewskie Lake, Laskownickie Lake) (Stefaniak et al. 2005).

The highly eutrophic state of Lake Łeknenskie was also confirmed by the presence of diatoms occurring during cyanobacterial blooms, such as *Ulnaria ulna*, *Navicula gregaria* Donkin, *Cyclotella radiosa* and *Nitzschia palea* (Kütz.) Smith, as they are indicators of hypereutrophy (van Dam et al. 1994). The presence of numerous chlorococcal green algae, although at the level of occasional species, also indicated the nature of highly eutrophic waters (Messyasz 2006). Despite the cyanobacteria presence in phytoplankton communities, the high average value of biodiversity at the level of 3.7 in the winter and spring confirmed a significant share of occasional species, especially diatoms and green algae. On the other hand, the presence of numerous euglenoids and cryptophytes in Lake Łeknenskie demonstrated the high content of organic matter in suspension (Celewicz-Gołdyn et al. 2010).

The zooplankton community was very poor and dominated by bacterivorous species of Rotifera, expressed in high TSI_{BAC} values (Table 2). The low numbers of filter feeding cladocerans such as *Daphnia* ssp. may be a consequence of the very high biomass of filamentous cyanobacteria, which are not suitable food for them. Filaments clog the filtering apparatus and hamper the feeding process of filter-feeders (Wejnerowski et al. 2015), causing a lack of some essential fatty acids (von Elert 2004). Thus, only smaller cladocerans that utilize other food sources can persist. The presence of *Chydorus sphaericus* in the pelagial zone is such an example, also indicating high trophy.

Nutrient loads

The primary cause of cyanobacterial water blooms in Lake Łeknenskie was high nutrient content, determined by both external and internal loading. The supply of nutrients with the waters of the inflowing the River Nielba played a crucial role in winter and early spring. These temporal variations in nutrient losses via stream discharge are determined by agricultural practices and weather-driven fluctuations (Gao et al. 2004). Loads from the agricultural areas which predominate in the catchment and insufficiently treated wastewater discharged from the village of Damasławek were the main sources of N and P.

In the case of the wastewater, P loads increased over three times in the ditch below the WWTP. This impact was also distinct in the River Nielba below the inlet of this ditch, where the P load increased 7 times. This impact was less distinct in the case of N because the studies were conducted during spring, when the release of N as nitrates from the agricultural areas is the most intensive (Szajdak et al. 2009). The loads of nutrients inflowing to Lake Łeknenskie at the time of the increased river water level in spring were comparable to the values noted in 2012 in the case of P (2.23 mg P d^{-1}), but significantly higher for N (over 300 kg N d^{-1}). However, the observed values were not extremely high in comparison with the loads discharged e.g. with the River Cybina (which is of a similar size) to Lake Swarzędzkie, reaching up to 139,922.8 kg N yr^{-1} and 1,954.5 kg P yr^{-1} (Kowalczewska-Madura 2003).

The comparison of N loads at the station below the WWTP in Damasławek and in the inlet to the lake indicated the occurrence of an additional, major source of N as the load at station 2 was 7–15% of the load inflowing to the lake. N outflow from the soil, clearly overfertilized with mineral forms of this compound, poses a threat to freshwater, therefore the adjacent location of big livestock farms producing liquid manure should not be permitted due to the negative impact on river and lake water quality (Fridrich et al. 2014).

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A comparison of the average P load reaching the lake from external sources (the river) and internal (the sediments) revealed that it was slightly higher in the case of internal loading. Both P sources show clear seasonal variations. Internal load obtains an advantage over the external load for most of the year, except winter (Table 5). A strong relationship between internal P loading and season was stated e.g. in the shallow Mona Lake, in which the loads from sediments contributed only 9% of the overall P load in spring but up to 82% in summer (Steinman et al. 2009).

The phenomenon of internal loading from bottom sediments played an important role in the lake during summer. An increased water temperature in this shallow, polymictic lake influenced both microbiological processes in the sediments and P release. The correlation between temperature and internal P loading is well known (Forsberg 1989) as a physical factor influencing organic matter decomposition. Additionally, P release was observed in aerobic conditions as lake waters were well oxygenated in the depth profile. Rapid, short-term thermal stratification, mixing caused by water turbulence and increased water flow velocity are crucial in shallow lakes (Søndergaard et al. 2001) as they may result in an orthophosphate concentration gradient in the water-sediment interphase, thus increasing P release. The occurrence of this process has been noted in many lakes in aerobic conditions (Kowalczewska-Madura et al. 2008, 2011, 2014; Kowalczewska-Madura and Gołdyn 2009; Gržetić and Čamprag 2010). In shallow lakes flux of P from the sediments into the water column is further increased by benthic macroinvertebrates (Ji et al. 2011).

The shallowness of a lake can lead to a P internal loading process similar to that in the littoral zone of deep lakes. Loading in the littoral area in the case of Lake Uzarzewskie reached up to 7 mg P m^{-2} d^{-1}, whilst in Lake Swarzędzkie it reached up to 22 mg P m^{-2} d^{-1}; both lakes are considered to be hypereutrophic (Kowalczewska-Madura and Gołdyn 2009; Kowalczewska-Madura et al. 2014). Moreover, in both lakes P release from bottom sediments was noted in colder seasons of the year, as in Łeknenskie Lake, which is typical of strongly eutrophicated lakes due to the lack of a hypolimnetic trap.

Lake management

The control of eutrophication and protection of aquatic ecosystems requires comprehensive water quality management, aimed initially at the reduction of external nutrient loads, which is considered to be the primary practical approach and the most imperative for water quality managers (Tang et al. 2016). However, the immediate consequences might be unpredictable, thus any technological solutions must be preceded by thorough and detailed analyses of environmental factors (e.g. hydrological/morphometric features of a water body and its catchment) as well as lake services from an economic aspect. Flow-through lakes are especially challenging due to their large catchment areas that determine multiple pollution sources (Dunalska et al. 2018).

The key for successful water quality management is the reduction of both nutrient sources i.e. external and internal. The decrease in external loads might be effective in spring but counterproductive in summer and autumn, when the phytoplankton blooms are controlled by loading from sediments (Lindim et al. 2015). Significant, permanent reduction of nutrient loads from the catchment might mitigate cyanobacterial blooms due to the gradual decrease of internal loads (less fresh organic matter on the surface of the sediments), however. this process would take many years with no certainty of success (Burger et al. 2008). In addition, there is a growing perception that combined reduction of both N and P is required to sufficiently improve ecological conditions in lake ecosystems (Lindim et al. 2015). For example, in the very large, shallow Taihu Lake in China it is expected that phytoplankton blooms expressed by 20 mg dm^{-3} of chlorophyll-*a* could be prevented only if the N and P loads diminish by 90% (Janssen et al. 2017).

N management seems to be much more complicated due to the diverse sources of nonpoint N loads, including nitrate leaching from soils and atmospheric deposition, being difficult to control (Finlay et al. 2013). More sustainable farming methods are necessary to reduce the TN loads supplying the River Nielba from the rural catchment (Gołdyn et al. 2015). A marked reduction in the amount of N released from the fields could also be achieved by the use of so-called biogeochemical barriers or denitrification walls (Świerk and Szpakowska 2013; Bednarek et al. 2014). The creation of artificial retention basins or wetlands along small ditches flowing into the River Nielba might reduce the nutrient inputs as well (Vymazal 2011; Mioduszewski 2012). Sorption materials e.g. ceramsite, have been proposed and tested recently, aiming at the purification of water in the upper river sections (Łopata et al. 2017). Undoubtedly, protective measures should be implemented in the whole catchment area, including the lakes situated upstream of Lake Łeknenskie and small tributaries of the River Nielba. Such a broad action plan of sustainable applications would require the co-operation of local authorities as well as farmers and other inhabitants, generating significant costs.

Most of all, the reduction of loads coming from the WWTP in Damasławek is crucial as its highly negative impact on nutrient concentrations in the River Nielba was clearly confirmed. An additional nutrient removal

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system is required, either as a part of the wastewater circulation in the WWTP (chemical precipitation), or other nature-based solutions e.g. ground filters. A similar solution has been used with great effect to protect Lake Sławskie (Western Poland) from treated municipal sewage, and proposed for wastewater management in Biały Bór (Northern Poland) (Dondajewska et al. 2018).

Another approach for through-flow lakes fed by very fertile river waters was proposed in the case of Lake Wolsztyńskie (Western Poland) i.e. the re-direction of the main tributary directly to the outflow (Dunalska et al. 2018). Such an approach would be possible in Lake Łeknenskie as the distance between the inflow and the outflow is less than 600 m, nevertheless, an economic justification would be necessary as well as a more detailed hydrological analyses, considering possible changes in lake water level fluctuations. The negative impact on lakes situated downstream of Lake Łeknenskie just 1.1 km away could be a serious disadvantage of this engineering project in the case of positive retention of nutrients in the studied lake. Therefore, nutrient balance should be calculated prior to the construction of any by-pass channel.

To reduce internal P loading it is necessary to apply restoration treatments that aim at the inactivation of P in bottom sediments. This is possible using chemicals like Phoslock or Sinobent (Gołdyn et al. 2014) in doses carefully selected to local conditions. Although sediment dredging appears to be a more effective method and is considered to be an option for shallow, hypertrophic lakes (e.g. Dunalska et al. 2015), it is usually much more destructive for the lake ecosystem, especially in the case of whole lake treatment. Sustainable restoration with P-binding agents would be more suitable for the analysed lake, on condition that its application is planned as a long-term treatment, which would require constant monitoring, especially in the case of P concentrations which determine the frequency of precipitation as well as chemical doses. This restoration method ought to be one of many in a comprehensive action plan, including biomanipulation as one of the nature-based methods. The current zooplankton structure indicated an adverse structure of fish fauna with the domination of planktivorous species. The increase of the predatory fish population, especially pike, should support water quality improvement, however, the lack of submerged macrophytes as well as the presence of large, filamentous cyanobacteria, might introduce feedback mechanisms responsible for delayed effects of lake stocking (Triest et al. 2016), thus recurrence is required. Additionally, in order to remove nutrients from outside the lake, some of the emergent macrophytes could be mowed, and their biomass removed (Ławniczak-Malińska and Achtenberg 2018). Such a treatment would create a mosaic of mowed and unmowed areas, and would be applied only with respect to the structure of the avifauna.

Conclusions

The functioning of the lake ecosystem is currently determined by substantial external loading, that should be reduced prior to the restoration process. Changes in wastewater treatment technology are crucial to decrease TP loading, while more sustainable farming is necessary to diminish TN loads from the rural catchment. A drastic reduction of external load could also be achieved by diversion of the River Nielba directly to the outflow of the lake, because it is located within a close distance. However, this would require more detailed analyses on nutrient balance, revealing whether the lake is a sink of source of nutrients for the river. In the latter case, there could be a very negative impact on the lakes situated below Lake Łeknenskie. Future restoration measures should be focused on the reduction of internal loading: P inactivation is necessary to reduce its internal loading from the bottom sediments. It should be implemented under a comprehensive action plan and supported by biological methods e.g. biomanipulation, macrophyte harvesting/planting.

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