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NITROGEN AND PHOSPHORUS LOADS IN THE RESTORED LAKE SAWAG

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Abstract: The aim of this study was to evaluate the ecological status of the restored Lake Sawag in the Olsztyn Lakeland. The analyzed water body was drained in the 19th century and converted into farmland. The former lake had an area of around 230 ha, and it was the largest drained water body in the Olsztyn Lakeland. The drained lake basin had been used as grassland until the 1990s when it was gradually filled with water due to the failure of outdated drainage systems. At present, Lake Sawag comprises three separate bodies of water with a combined area of 106 ha. Its catchment is used for agricultural purposes which, in view of the lake's small depth, poses a serious threat of degradation to the aquatic environment. The described study was conducted during four hydrological years of 2008 to 2011, and it covered three constituent sections of the contemporary Lake Sawag: northern (62 ha), central (14 ha) and southern (30 ha). Water samples were collected eight times in each year of the study, and they were analyzed to determine the concentrations of: nitrites(III), nitrates(V), ammonia nitrogen, total nitrogen, total phosphorus and dissolved phosphates. The following parameters were also measured: oxygen concentrations, pH, electrolytic conductivity, chlorophyll a and turbidity levels in water samples. The results of the above analysis point to low water quality in the restored lake. All sections of the studied water body were characterized by high electrolytic conductivity (average of 403 $\mu S \cdot cm^{-1}$), highly excessive phosphorus levels (0.30 $mg \cdot dm^{-3}$) and intensive phytoplankton blooms. The example of Lake Sawag indicates that although restoration projects generate numerous advantages for the ecosystem (protection of water resources, scenic value, fishing), they are susceptible to degradation and difficult to maintain in a satisfactory ecological condition.

Keywords: restored lake, rural catchment, nitrogen, phosphorus, eutrophication

Shallow (polymictic) lakes are the predominant type of water bodies found in the lake districts of northern Poland [1]. They differ from deep water bodies with regard to their functional attributes, in particular the absence of thermal stratification in the summer [2, 3]. Most shallow lakes are highly susceptible to degradation [3, 4]. The above results from internal factors (small depth and volume, contact with bottom deposits, resuspension of sediments due to near-bottom wave motion and activity of

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benthic organisms) as well as external influences (inflow of organic matter from the catchment) which contribute to eutrophication. Thermal stratification, a phenomenon encountered in deeper lakes in the summer, is not observed in shallow water bodies and, as a result, the entire water column of a shallow lake undergoes complete mixing. Bottom deposits are activated, and nutrients are exchanged between sediments and water. Shallow lakes are also susceptible to resuspension which enhances internal loading – the movement of biogenic substances from bottom deposits into water [5].

The functioning of shallow lakes is described by the theory of alternative stable states [6–8] in the light of which, an aquatic ecosystem may become permanently dominated by phytoplankton (stable state of turbid water) or macrophytes (state of clear water). Highly fertile lakes of the moderate climate zone are unlikely to be dominated by submerged macrophytes [3, 7]. A stable state of macrophyte domination can be achieved in degraded lakes only through radical restoration efforts that limit external load (biomanipulation, phosphorus inactivation) and break the predominance of phytoplankton in the ecosystem [9]. Measures which increase a lake's resistance to degradation, such as increasing water volume through water accumulation or ponding, may have a beneficial effect on the ecological status of shallow water bodies [3, 7]. In extreme cases, water accumulation can lead to the restoration of a dried water body, as in Lake Sawag. According to Scheffer [7], there is a general scarcity of published data about lakes that had existed as dry basins for long periods of time. Information about the underlying mechanisms and course of eutrophication in restored lakes is, therefore, vital from both scientific and practical points of view.

The objective of this study was to evaluate the ecological status of the restored Lake Sawag in the Olsztyn Lakeland. The analyzed water body had been drained and converted into grassland in the 19th century. The lake was partially restored relatively recently, therefore, the results of our study could provide valuable insights into the initiation of trophic processes in a "young" water body.

Materials and methods

The object of our study was Lake Sawag in the municipality of Swiatki in the Olsztyn Lakeland (53°58′36″ N, 20°18′51″ E). In the 19th century, the lake was drained and converted into meadows. Prior to the drainage project, Lake Sawag had a much higher water level and a surface area of around 230 ha (Fig. 1), rendering it the largest drained water body in the Olsztyn Lakeland [10]. The analyzed water body is marked as Lake Sawanna in 18th century maps, and prior to drainage in the 19th century, it was known as Lake Sawag or Legnowskie [11]. The drainage effort took place in 1870–1871, and it led to the lake's complete disappearance. The basin had been used as grassland (partially water-logged) until the 1990s when it was gradually filled with water due to the failure of outdated drainage systems.

According to reference data, the southern and central parts of the lake were restored in 1994–1995, and the northern part – around the year 2000. During the period of the study, the "new" Lake Sawag was a young body of water characterized by weakly developed aquatic vegetation and rush plants.

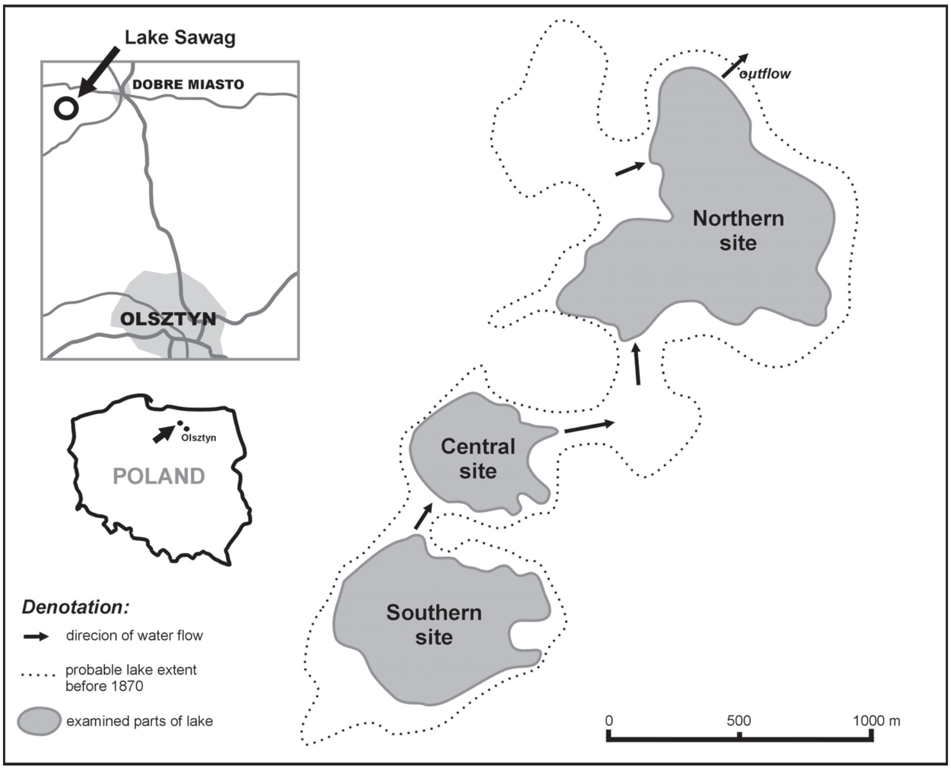

Fig. 1. Location of the analyzed site with a division into constituent sections (source: own study)

At present, Lake Sawąg has an area of 106 ha, and it comprises three distinct water bodies (Fig. 1) connected by a system of open ditches: the northern (62 ha), central (14 ha) and southern (30 ha) sections situated at the altitude of 109 (northern section) and 109.5 m above sea level (southern and central sections).

The catchment of the former lake has an area of 755 ha, 90 % of which is used for farming purposes. Partial catchments are separated into three parts which correspond to the three contemporary sections of the lake. Built-up areas cover 4.3 % of the catchment area of the northern section of the lake: they are the village of Legno with a population of 400 and a residential estate formerly administered by a State Agricultural Farm. In addition to surface runoffs, a small water course exiting the village and the estate is the main source of pollution in the analyzed lake. Village Legno and the northern section of the lake are separated by an additional body of water which constituted a separate site in the first years after the lake's restoration, but due to rising water levels, it was joined with the northern section of Lake Sawag. Forests cover 4 % of the catchment area, and they are limited to a cluster of trees in the central section of the lake and green belts along its shore. The layout of certain afforested fragments seems to reflect the lake's original shoreline before it was drained 140 years ago (Fig. 1).

The study was carried out in the course of four hydrological years of 2008 to 2011, and it covered three contemporary sections of Lake Sawag: northern, central and southern. Each year, water samples were collected eight times at equal time intervals – two samples in the spring, summer, fall and winter season. They were analyzed to determine the concentrations of: nitrites(III), nitrates(V), ammonia nitrogen, total nitrogen, total phosphorus and dissolved phosphates. All analyses were carried out in the laboratory of the Department of Land Improvement and Environmental Management at the University of Warmia and Mazury in Olsztyn, with the involvement of standard analytical methods. In-situ measurements were also performed to determine oxygen concentrations, pH, electrolytic conductivity, chlorophyll a and turbidity levels in water samples, with the use of the YSI 6600 multi-parameter probe.

Results

The results of evaluations carried out in 2008–2011 revealed a poor ecological status of Lake Sawag, in particular high phosphorus concentrations which are responsible for eutrophication. Selected water quality parameters (Table 1) were indicative of a disturbed ecosystem, but the average values of analyzed indicators remained relatively stable in successive years of the study. The lake was characterized by satisfactory oxygen concentrations with a distinctive rise in dissolved oxygen levels on a seasonal basis.

Table 1

Average values and standard deviation of selected water parameters in the southern, central and northern sections of Lake Sawag in 2008–2011

Site	Year	Parameter / Value (standard deviation)				
		Dissolved oxygen [%]	pH range	Conductivity [$\mu S \cdot cm^{-1}$]	Chlorophyll a [$\mu g \cdot dm^{-3}$]	Turbidity [NTU]
Southern	2008	90.4 (±10.5)	7.71–8.74	417 (±22.4)	34.9 (±20.5)	6.2 (±1.7)
	2009	109.4 (±24.2)	7.56–8.13	425 (±20.5)	29.9 (±10.1)	6.1 (±3.9)
	2010	103.2 (±21.7)	7.07–8.97	404 (±76.3)	21.5 (±16.3)	13.6 (±16.7)
	2011	100.1 (±22.1)	7.64–8.88	389 (±10.2)	24.3 (±13.7)	10.5 (±6.9)
	2008–2011	**100.8 (±20.5)**	**7.07–8.97**	**410 (±42.2)**	**27.8 (±15.8)**	**9.1 (±9.5)**
Central	2008	108 (±29.8)	7.75–8.83	386 (±23.8)	33.8 (±14.8)	6.9 (±4.6)
	2009	93.9 (±24.6)	7.53–8.18	413 (±25.2)	26.1 (±14.1)	5.4 (±4.1)
	2010	98.1 (±23.7)	7.14–9.00	412 (±57.9)	30.1 (±19.0)	7.9 (±5.9)
	2011	109.6 (±22.8)	7.72–8.92	396 (±19.1)	41.3 (±25.1)	6.0 (±2.4)
	2008–2011	**102.2 (±25.1)**	**7.14–9.00**	**402 (±35.7)**	**32.6 (±18.4)**	**6.6 (±4.4)**
Northern	2008	87.1 (±13.4)	7.85–8.76	428 (±26.9)	26.3 (±10.6)	7.8 (±9.2)
	2009	124.7 (±38.1)	7.61–8.15	382 (±44.1)	40.4 (±21.6)	11.6 (±9.3)
	2010	110.6 (±27.4)	7.25–8.86	377 (±76.0)	32.2 (±19.3)	14.5 (±16.6)
	2011	104.1 (±26.9)	7.79–8.74	395 (±21.8)	22.5 (±6.5)	5.4 (±1.3)
	2008–2011	**106.7 (±29.9)**	**7.25–8.86**	**396 (±49.8)**	**30.6 (±16.6)**	**10.0 (±10.8)**

Extreme oxygen concentrations reached 150 % in the southern section, 172 % in the central section and 200 % in the northern section of the lake. Oxygen saturation exceeded 65 % in all water samples, including in the winter. Winter anoxia, which is characteristic of excessively productive water bodies, was not observed due to large quantities of phytoplankton, including in the coldest months of the year.

Electrolytic conductivity remained fairly stable during the experimental period, and no significant variations were reported between the evaluated sections of the lake. Electrolytic conductivity values were generally high, which is usually the case in polymictic water bodies and catchment areas that are used for agricultural purposes. In line with the criteria for evaluating the quality of lake water [12], electrolytic conductivity exceeded the norm (>350 $\mu S \cdot cm^{-1}$) in all sections of the water body and in all seasons. The average values throughout the period of the study (410 $\mu S \cdot cm^{-1}$ in the southern section, 402 $\mu S \cdot cm^{-1}$ in the central section and 396 $\mu S \cdot cm^{-1}$ in the northern section) were significantly higher than those noted in Lake Nowe Wloki, a water body with a similar transformation history (it was reclaimed in the 19th century and restored in later periods). Twenty years after restoration, the average electrical conductivity in Lake Nowe Wloki was 233 $\mu S \cdot cm^{-1}$ [13].

Lake Sawag was characterized by high chlorophyll a levels which remained relatively stable during the four-year period of the study. Average chlorophyll a concentrations of 30 $\mu g \cdot dm^{-3}$ testify to high productivity levels. The values of the above parameter were similar in all sections of the water body, and they did not deviate significantly from average values in each season. Chlorophyll concentrations were also high under ice cover in the winter. Lake Sawąg has a stable phytoplankton community structure, with cyanobacteria as the predominant primary producers in the ecosystem. Water turbidity was high and stable in 2008, 2009 and 2011, whereas significantly higher turbidity levels were reported in 2010 (Table 1). In the summer of 2010, water temperature exceeded 25 °C and extensive cyanobacteria blooms contributed to the achievement of maximum turbidity values in all sections of the lake at 38.6 NTU in the southern section, 19.2 NTU in the central section and 42.9 NTU in the northern section of the water body. During that period, Secchi disc visibility in the northern section decreased considerably to 0.35 m.

Lake Sawag was moderately abundant in nitrogen compounds. Average total nitrogen concentrations insignificantly exceeded threshold values to reach 2.05 $mg \cdot dm^{-3}$ in the southern section, 2.13 $mg \cdot dm^{-3}$ in the central section and 2.44 $mg \cdot dm^{-3}$ in the northern section of the lake (Fig. 2). Clearly higher average nitrogen levels in the southern part could be attributed to the presence of built-up areas in the catchment area and the fact that it was the youngest section of the restored lake. In the summer and fall, high nitrogen concentrations were the result of intensive cyanobacteria blooms. In the above periods, nearly 90 % of nitrogen occurred in organic form. The organic form was also predominant in the remaining seasons, and the share of dissolved mineral forms did not exceed 20 % (Fig. 3). Average concentrations of mineral nitrogen reached 0.30 $mg \cdot dm^{-3}$ in the southern section, 0.34 $mg \cdot dm^{-3}$ in the central section and 0.31 $mg \cdot dm^{-3}$ in the northern section. Ammonia nitrogen accounted for 2/3 of the above values on average. Unlike phosphorus, moderate N-min levels (water quality class II) were also observed in the growing season. Similarly to Lake Nowe Wloki [14], the lowest mineral nitrogen concentrations were reported in the spring, but in Lake Sawag, mineral nitrogen levels were considerably lower throughout the year.

The phosphorus limits for waters not meeting quality standards (0.20 mg · dm^{-3}) were significantly exceeded in Lake Sawag. The average phosphorus concentrations

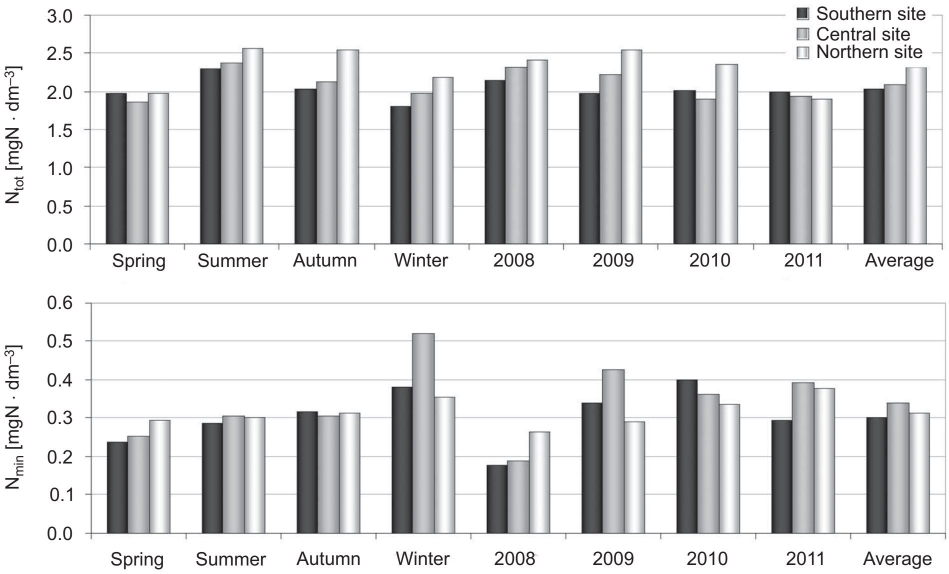

Fig. 2. Total nitrogen (N_{tot}) and mineral nitrogen (N_{min}) concentrations in three sections of Lake Sawag – seasonal, annual and average values for the entire period of the study (2008–2011)

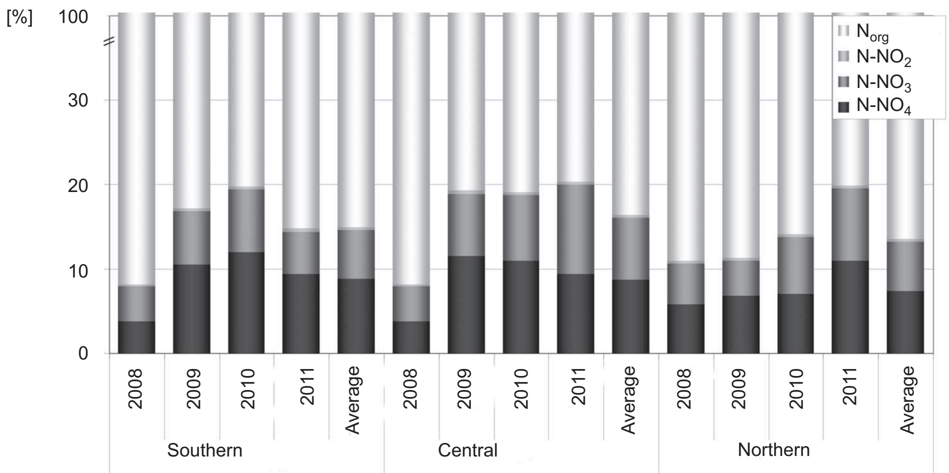

Fig. 3. Share of different nitrogen forms in the water of the studied sections of Lake Sawag in 2008–2011

over the period of the study reached 0.29 mg · dm^{-3} in the southern and northern sections and 0.31 mg · dm^{-3} in the central section (Fig. 4). Nearly 80 % of phosphorus occurred in organic form, but high phosphate levels were noted in the summer and fall. The above points to highly excessive amounts of phosphorus in circulation. As a result, primary production in the ecosystem was not nutrient (phosphorus) limited. If that were the case, the widespread growth of phytoplankton could have been prevented [7]. Average phosphorus levels were nearly 50 % higher in comparison with Lake Nowe Wloki [14], but unlike in the latter, very high phosphorus concentrations were maintained in Lake Sawag also in the fall. In the analyzed water body, excessive phosphorus content was probably the main factor preventing a natural improvement in the ecological status of the restored lake. According to research data [15], the maintenance of a clear water status requires phosphorus loads that do not exceed 0.10 mg · dm^{-3}. In Lake Sawag, the above level was more than twice higher in the spring and winter, and it reached nearly 0.40 mg · dm^{-3} in the summer and fall in all three sections of the water body (Fig. 4).

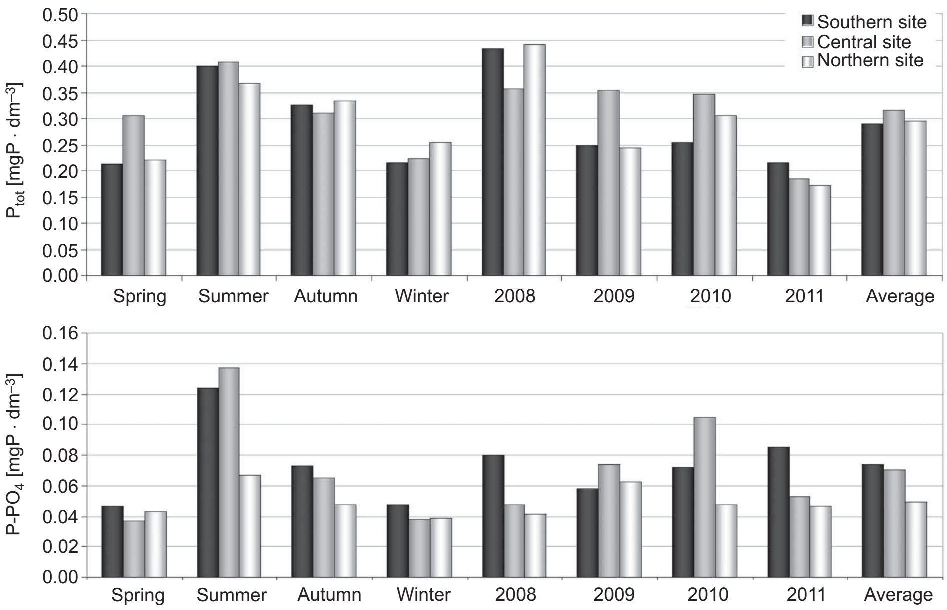

Fig. 4. Total phosphorus (P_{tot}) and phosphate (P-PO_4) concentrations in the water of the studied sections of Lake Sawag – seasonal, annual and average values for the entire period of the study (2008–2011)

Lake Sawag had remained dry for more than a century, and only around 50 % of its original area was restored. At the beginning of the study, it was a relatively young water body – the southern and central sections had existed for 12–13 years, and the northern section – for 7 years. The results of our assessment indicate that the major component of the restored ecosystem were phytoplankton communities and that macrophytes played a minor role as primary producers. High levels of phosphorus contributed to the stable growth of phytoplankton. Based on phosphorus concentrations in the experimental period, all three sections of the lake were classified as hypertrophic water bodies (Table 2). Trophy levels varied across different years of the study, excluding the smallest central section where phosphorus loads remained radically high throughout the entire experiment. Based on phytoplankton-related parameters (chlorophyll a concentrations and Secchi disk visibility), the sections of Lake Sawag were classified as eutrophic to polytrophic water bodies. With a steady supply of mineral phosphorus, the lake probably achieved a state of ecological balance in which primary production was inhibited by the limited availability of light. The above is characteristic of lakes with a stable turbid-water state.

Table 2

Trophy levels in the studied sections of Lake Sawag in 2008–2011:
southern (Sth), central (Ctr) and northern (Nth), based on [16];
trophy levels: E – eutrophic, P – polytrophic, H – hypertrophic (> 100 % threshold of polytrophy)

Site	Period	N_{tot} (Spring)		P_{tot} (Spring)		Chorophyll *a* – mean (Annual)		Chlorophyll *a* – max.		Secchi depth – mean (Annual)		Secchi depth – min	
		Value	State	Value	State	Value	State	Value	State	Value	State	Value	State
Sth	**Average 2008–11**	**1.97**	**P**	**0.21**	**H**	**27.8**	**P**	**51.9**	**E**	**1.09**	**E**	**0.67**	**P**
	2008	2.12	P	0.45	H	34.9	P	68.3	E	1.04	E	0.76	E
	2009	1.91	P	0.16	P	29.9	P	47.8	E	1.16	E	0.79	E
	2010	1.77	P	0.08	E	21.5	E	51.5	E	1.18	E	0.47	P
	2011	2.08	P	0.16	P	24.3	E	39.9	E	0.97	P	0.64	P
Ctr	**Average 2008–11**	**1.87**	**P**	**0.30**	**H**	**32.6**	**P**	**67.7**	**E**	**1.11**	**E**	**0.70**	**E/P**
	2008	2.02	P	0.44	H	33.8	P	64.0	E	1.05	E	0.58	P
	2009	1.48	E	0.24	H	26.1	P	46.6	E	1.21	E	0.73	E
	2010	1.88	P	0.33	H	30.1	P	68.7	E	1.09	E	0.57	P
	2011	2.09	P	0.21	H	41.3	P	91.4	P	1.09	E	0.92	E
Nth	**Average 2008–11**	**1.98**	**P**	**0.22**	**H**	**30.6**	**P**	**50.7**	**E**	**1.05**	**E**	**0.63**	**P**
	2008	2.05	P	0.38	H	26.3	P	47.4	E	1.17	E	0.59	P
	2009	1.60	P	0.14	P	40.4	P	72.1	E	0.90	P	0.58	P
	2010	2.27	P	0.18	P	32.2	P	54.9	E	1.02	E	0.37	P
	2011	2.01	P	0.18	P	22.5	E	28.5	E	1.12	E	0.97	E

An N : P supply ratio below threshold values (Fig. 5A) and a high average ratio of phosphorus to chlorophyll a concentrations (Fig. 5B) are also indicative of excessive phosphorus concentrations in Lake Sawag. It is assumed that a P : Chl ratio of 3 : 1 is the threshold value supporting a shift between stable states (phytoplankton and macrophyte) [6, 7]. In the analyzed lake, the above balance was significantly tipped in favor of phosphorus, and the average P : Chl ratio was determined at 8.64 : 1 (Fig. 3). After the first three years of the study, significant similarities in P : Chl ratio values were noted in the southern and central sections (9.8 : 1 and 9.7 : 1, respectively), whereas the share of phosphorus was lower in the northern section of the lake (6.9 : 1).

Following intensive phytoplankton blooms in 2011, the P : Chl ratio in the central section approximated the values noted in the northern part of the water body (Fig. 5B). The above change provides further evidence of excessive phosphorus levels in the ecosystem, pointing to a long-lasting steady state of phytoplankton in the lake.

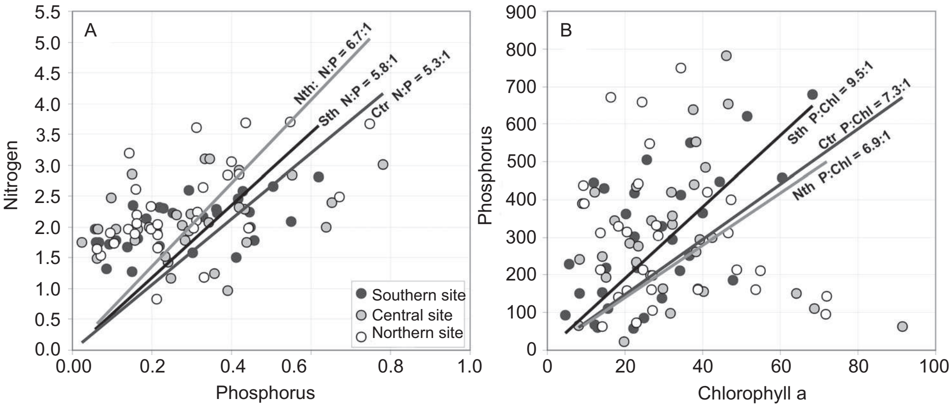

Fig. 5. Nitrogen to phosphorus ratio (A) and phosphorus to chlorophyll a ratio (B) in the studied sections of Lake Sawag, based on data acquired in 2008–2011

An improvement in the ecological status of shallow lakes is difficult to achieve because it requires a reduction in both external and internal sources of nutrient supply [3]. According to published data, the achievement of a clear-water state requires the elimination of algal blooms. Such a state occur in lakes where macrophytes, in particular submerged plants, act as primary producers. In Lake Sawag, phytoplankton communities, mostly cyanobacteria, were the predominant group of primary producers throughout the entire period of the study. Phytoplankton growth is the key contributor to turbidity, and this problem is very difficult to eliminate. Excessive proliferation of cyanobacteria was observed in the summer and fall, the above increased turbidity levels while chlorophyll a concentrations remained high and stable.

In shallow lakes, internal nutrient supply and phytoplankton blooms may neutralize the protective effects of reduced pollutant supply from external sources. The movement of biogenic substances from bottom deposits to water becomes the main supply mechanism for primary producers. Massive growth of phytoplankton additionally contributes to this process. The assimilation of biogenic substances, in particular phosphorus, leads to nutrient depletion, and the resulting deficit initiates the diffusion of additional sources from bottom deposits [17]. In Lake Sawag, those processes were additionally reinforced by an absence of land obstacles which would protect the lake from wind. The above leads to intensive wave motion which further contributes to sediment resuspension and inhibits lake colonization by vascular plants. Those negative effects could be somewhat alleviated by planting rows of trees along the shoreline which would act as barriers against external sources of pollution.

Restored lakes are a special example of shallow lake ecosystems [3]. Steady-state phytoplankton assemblages are likely to colonize a water body shortly after its restoration in a farmland. A high supply of biogenic substances from the catchment area and ecosystem hysteresis preserves the steady-state ecosystem [18]. The results of our study indicate that Lake Sawag has found itself in a "eutrophication" trap which will be difficult to escape in the course of its evolution. The lake's water level continues to rise, and an increase of approximately 0.5 m was noted during the four-year study. Rising water levels increase the lake's surface area and shift its shoreline. The noted changes suggest that the lake restoration process is likely to continue in the future, which should be regarded as a positive sign. Protective measures aiming to reduce the supply of organic matter from the catchment cannot be planned, however, until the lake's hydrological regime has been stabilized.

Conclusions

1. Lake Sawag, a recently restored water body that had remained dry for more than a century, was studied between 2008 and 2011. It was characterized by high trophy levels as well as high concentrations of chlorophyll a, phosphorus and nitrogen.

2. The analyzed ecosystem revealed symptoms of alternative steady-state phytoplankton growth with the predominance of cyanobacteria. In shallow, with an abundant supply of biogenic substances, the above may limit the effectiveness of protective measures aiming to reduce nutrient supply from the catchment.

3. The restoration of formerly dried lakes could improve the quality of water resources in catchment areas used for agricultural purposes. The example of Lake Sawag, the largest water body of the Olsztyn Lakeland dried in 19^{th} century, indicates that restored lakes are highly susceptible to degradation. Excessive phosphorus concentrations seem to be the main obstacle to an improvement in the lake's ecosystem.

Acknowledgements

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Abstrakt: Celem pracy była ocena stanu przekształconego jeziora Sawąg, położonego na Pojezierzu Olsztyńskim. Obiekt należy do jezior, które w XIX wieku zostały osuszone z przeznaczeniem na grunty rolnicze. Wcześniej jezioro miało powierzchnię około 230 ha, co kwalifikuje je jako największe odwodnione jezioro Pojezierza Olsztyńskiego. Po osuszeniu teren zagłębienia utrzymywany był jako łąki aż do lat 90. XX w., kiedy zbiornik zaczął się stopniowo odtwarzać w wyniku pogorszenia się drożności urządzeń melioracyjnych. Obecnie jezioro Sawąg składa się z trzech oddzielnych akwenów o łącznej powierzchni 106 ha. Obiekt charakteryzuje rolniczym użytkowaniem zlewni, co przy niewielkiej głębokości zbiornika powoduje jego znaczne zagrożenie degradacją. Badania prowadzono w ciągu czterech lat hydrologicznych 2008–2011 i objęto nimi 3 akweny, z których współcześnie składa się jezioro Sawąg: północny (62 ha), centralny (14 ha) i południowy (30 ha). Próbki wody do badań pobierano 8-krotnie w każdym roku i oznaczano w nich: azotany(III), azotany(V), azot amonowy, azot ogólny oraz fosfor ogólny i fosforany rozpuszczone. Dodatkowo mierzono koncentrację tlenu, odczyn, przewodność elektrolityczną, chlorofil a i mętność. Badania wykazały, że stan jeziora Sawąg po przywróceniu zwierciadła wody był niekorzystny. Wszystkie akweny cechowały się wysoką przewodnością elektrolityczną (średnio 403 μS $\cdot$ cm^{-1}) i ogromnym nadmiarem związków fosforu w ekosystemie (0.30 mg $\cdot$ dm^{-3}), a przez to tendencją do intensywnych zakwitów fitoplanktonu. Przykład jeziora Sawąg wskazuje, że renaturyzacja dawnych jezior, obok wielu korzyści (ochrona zasobów wodnych, walory krajobrazowe, wędkarstwo i inne), przynosi również poważny problem utrzymania ich stanu ekologicznego.

Słowa kluczowe: renaturyzacja jezior, zlewnia rolnicza, azot, fosfor, eutrofizacja