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SEASONAL CHANGES OF NUTRIENTS CONCENTRATION IN TWO SHALLOW ESTUARINE LAKES GARDNO AND ŁEBSKO; COMPARISON

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Abstract

The aim of this paper was the presentation and comparison of seasonal biogens changes and trophy state classification of two biggest shallow coastal lakes Gardno and Łebsko, located in the northern part of Poland, along the southern coast of the Baltic Sea.
Measurements were conducted once a month from April to December 2007. For the purpose of this article at each lake one measurement station was selected, to represent well mixed area of the lakes, far from outlet to the sea and rivers. Performed measurements showed that the lakes are similar. The differences, observed between biogens concentration in lakes were statistically insignificant. Seasonal dynamics of nutrients concentration in lakes indicated that the lakes are typical shallow lakes. Moreover, the summer concentration of total nitrogen and phosphorus qualify these lakes as eutrophic.

Key words: shallow lake, phosphorus, nitrogen, eutrophication

INTRODUCTION

Shallow estuarine lakes are very dynamic water ecosystems with constant fluctuations in physical and chemical parameters. As opposed to more often-studied deeper, dimictic inland lakes they are characterized by: (i) a lack of stable long-term thermal stratification, (ii) frequent mixing of entire water column, (iii) substantial internal loading of nutrients from the sediments to water column. However each of these lakes considerably differs one from another. The differences are associated with the distance in straight line of the lake basin to the sea and the intensity strength of the sea, morphometric parameters, coefficient of exposure, and the quality of lake basin i.e. anthropopression level (Cieśliński 2004, Trojanowski 1990, Trojanowski et al. 1991).
At the Polish Baltic Coast are many estuarine smaller or bigger lakes such as: Bukowo, Jamno, Kopań, Wicko, Dołgie Wielkie, Gardno, Łebsko, and despite a similar

genesis and geomorphological type (Paturej 2006) they differ in hydrological and hydrochemical conditions.
The aim of this paper is the presentation and comparison of: (i) general properties of two shallow coastal lakes Gardno and Łebsko, (ii) seasonal biogens changes in both lakes, and (iii) current trophy state classifications.

MATERIAL AND METHODS

Studies area

The studies were carried out in two estuarine lakes: Gardno (54°39,4′; 17°07,1′) and Łebsko (54°42,8′; 17°24,7′), located in the northern part of Poland along the southern coast of the Baltic Sea (Fig. 1). The lakes constitute part of the Slovinski National Park, and are the two largest coastal lakes.
The low depth, large surface area, and good exposure to winds (Tab. 1) enable a full mixing of lakes water in vertical profile. As a result these lakes are regarded as

Table 1
Morphometric parameters of lakes (source Atlas jezior... 1997)

Parameter	Lake	
	Gardno	Łebsko
Area, km^2	24.68	71.40
Volume, thous. m^3	30950.5	117521.0
Mean depth, m	1.3	1.6
Maximum depth, m	2.6	6.3
Shoreline, km	23.35	55.88
Exposure coefficient	1898.5	4462.5
Altitude, m	0.3	0.3
Development of shoreline	1.33	1.87

polymictic basins in which no thermal or oxygen stratification is observed (Trojanowski et al. 1991, Trojanowski 2003a). Moreover, published data (Cydzik and Soszka 1988, Atlas jezior... 1997, Trojanowski et al. 1991) showed that both lakes are susceptible to degradation and high nutrient concentrations caused that lakes were classified as eutrophic.

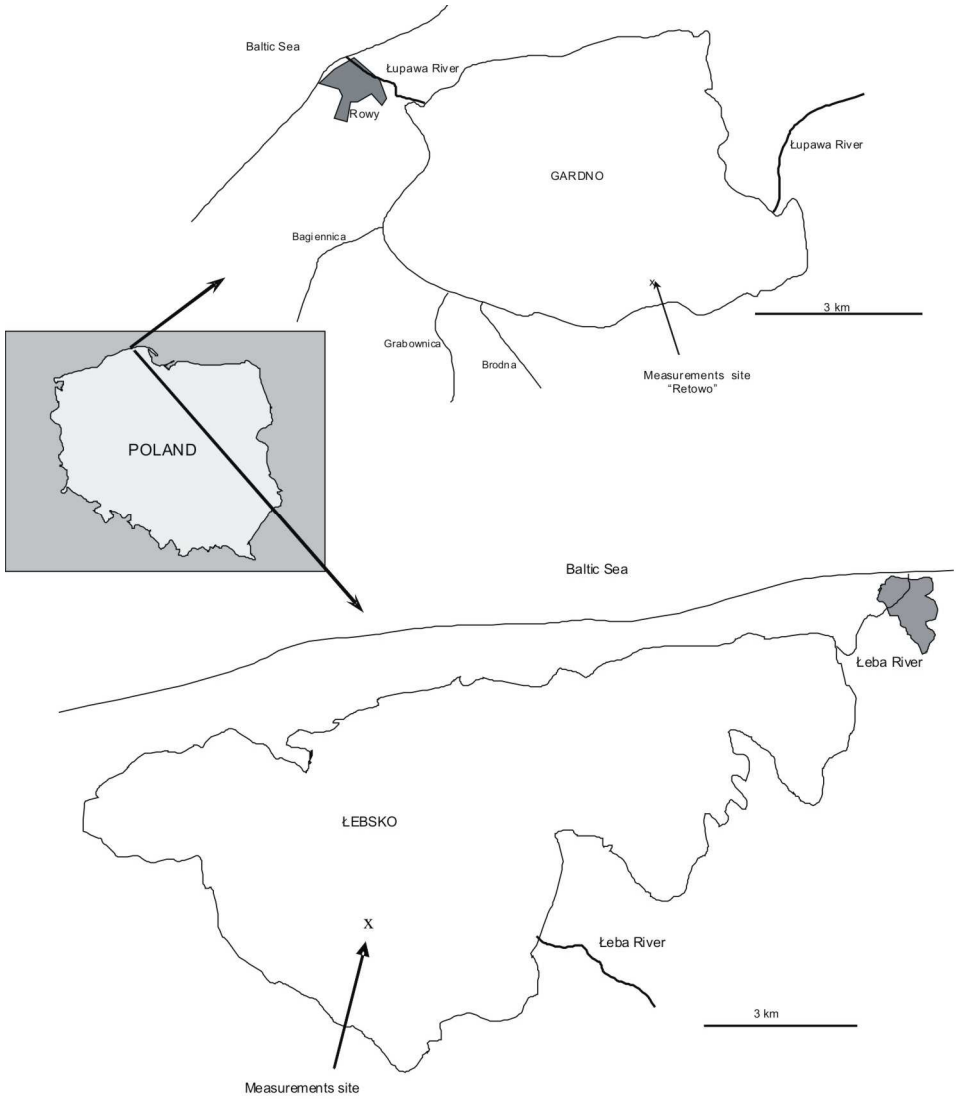

Fig. 1. Location of sampling stations in lakes Gardno and Łebsko

Lake Gardno

Lake Gardno is connected with the Baltic Sea through the Łupawa Channel of about 1500 m length and separated from the sea water by a sandy bar 800-2000 m wide (Trojanowski 2003b). Gardno is supplied by the water of the Łupawa River and several smaller rivers: Bagiennica, Grabownica, Brodniczka and Brodna. The total riverine inflow to the lake was estimated at 9.07 m s^{-1}. It is about $286 \cdot 10^6$ m^3 yearly,

but the Łupawa River supplies about 90% of all surface water inflow into the basin. A total water exchange in the lake occurs over 9 times a year (water exchange index 9.2).
Lake Gardno is shallow, with the average depth about 1.3 m (maximum depth 2.6 m). The lake surface covers a large area of about 25 km^2. The emergent macroflora covers 4% of the lake's surface forming offshore belt 20-200 m wide, which constitutes a residence for many bird species. Because of terrestrial runoff from its rural surroundings and by sewage discharge from the holiday resort of Rowy in to the lake, throughout the whole vegetation season an algal bloom is observed (Mudryk and Skórczewski 2004).

Lake Łebsko

Lake Łebsko is connected with the sea through the Łeba Channel (2800 m) and the distance of the lake reservoir from the shoreline of the Baltic Sea is 600 m (Cieśliński 2004). Like the majority of coastal lakes it is characterized by a large area of 71.4 km^2. The volume of lake amounts to about $117.5 \cdot 10^6$ m^3, the mean depth is 1.6 m and the maximum depth 6.3 m (Atlas jezior... 1997). Several rivers discharge into the lake, of which the dominant is the Łeba River. The total inflow to the lake was estimated at 16.9 m^3 s^{-1}. It is about $533 \cdot 10^6$ m^3. The water exchange coefficient of 4.4 reassures a high dynamic of water exchange during a year (Chlost and Cieśliński 2005).
Lake Łebsko is not direct sewage receiver from point sources, but into the lake flow riverine waters (the Łeba River) abounding with biogens.

Measurements

Measurements presented in this paper were conducted once a month from April to December 2007. For the purpose of this article at each lake one place was selected, at which the water samples were collected (Fig. 1). The stations were selected based on many measurements of water parameters (i.e. salinity, conductivity, biogens concentration) performed in years 2006-2007 (Jarosiewicz and Ficek 2008) to represent well mixed area of the lakes, far from outlet to the sea and the Łupawa River and the Łeba River in Gardno and Łebsko, respectively.
The water column in the lakes was very homogeneous therefore the samples were collected from subsurface layer.
Concentrations of respective nutrient forms: (NH_4^+-N, NO_3^-N, N-total, PO_4^-P, P-total) were measured in the laboratory using standard colorimetric methods (Fizyczno-chemiczne... 1976). Amount of organic forms of N and P was calculated as a difference between the concentration of total and mineral forms. The pH and electrical conductance (EC) measurements were performed by potentiometric and conductometric methods respectively, using adequate electrodes.

RESULTS

The water conductivity was changed (Fig. 2) in both lakes during the measurements period, and it is difficult to determine the seasonal trend of changes. In the Gardno Lake the water conductivity varied from 0.62 mS in June to 3.19 mS in November (average 1.74 mS), whereas in Łebsko the average conductivity was about 60% higher and amounted 2.87 mS. The minimum was observed in July, the maximum, similar to Gardno in November – 4.26 mS. The mean annual salinity, at measurement stations, amounted to 0.96 and 1.58 in Gardno and Łebsko, respectively.

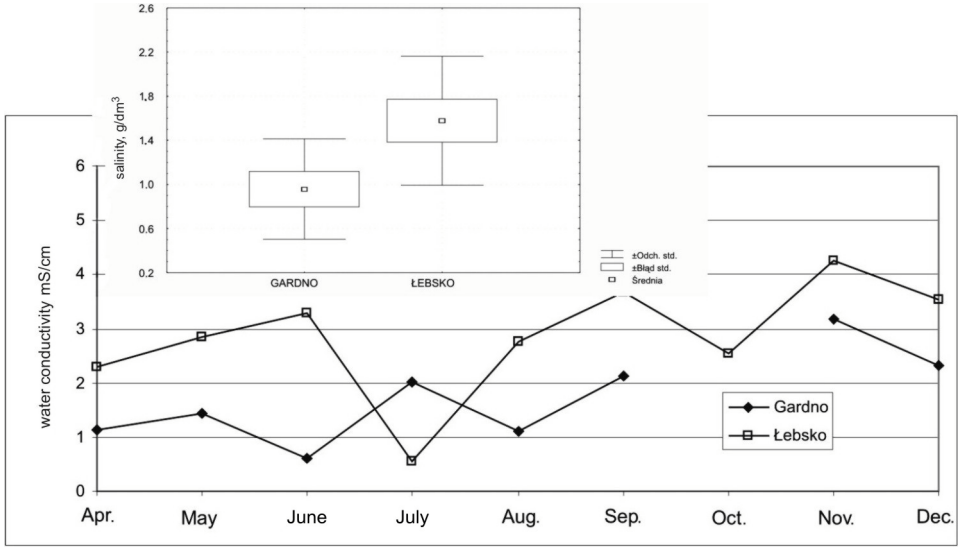

Fig. 2. Water conductivity and salinity in lakes Gardno and Łebsko

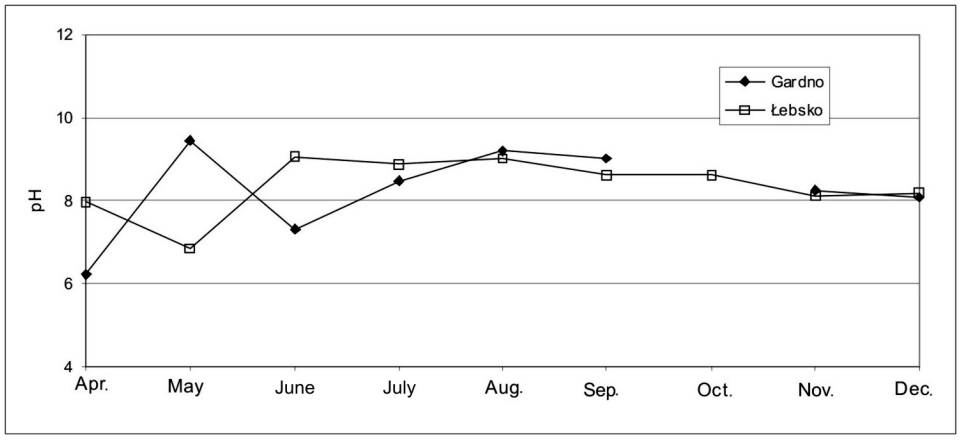

Fig. 3. Seasonal changes of pH value in lakes Gardno and Łebsko

The pH (Fig. 3) value was in the whole research period high, and except April (Gardno) and May (Łebsko) amounted to above 8. Moreover, the changes of pH value were similar in both lakes, i.e. in summer higher than in autumn-winter period.

It was observed that the phosphates concentrations (mgP/dm^3) were relatively stable during the research period (Fig. 4a). Mean mineral P-concentration was similar in the lakes and amounted to 0.041 mgP/dm^3 in Gardno and 0.042 mgP/dm^3 in Łebsko. In both cases the systematic loss of mineral phosphorus in epilimnion during the vegetative period, typical of deeper lakes, was not observed. The summer minimum, noted in both lakes in June (the concentration decreased to about 0.02 mgP/dm^3) was short-lived. The concentration of total P (Fig. 4b) in the Gardno lake averaged 0.173 mgP/dm^3±0.076, and almost through whole measurement period was relatively stable. Only during late autumn and winter the higher concentrations of P-total were observed. Moreover, compared with spring the slight increase of total phosphorus in

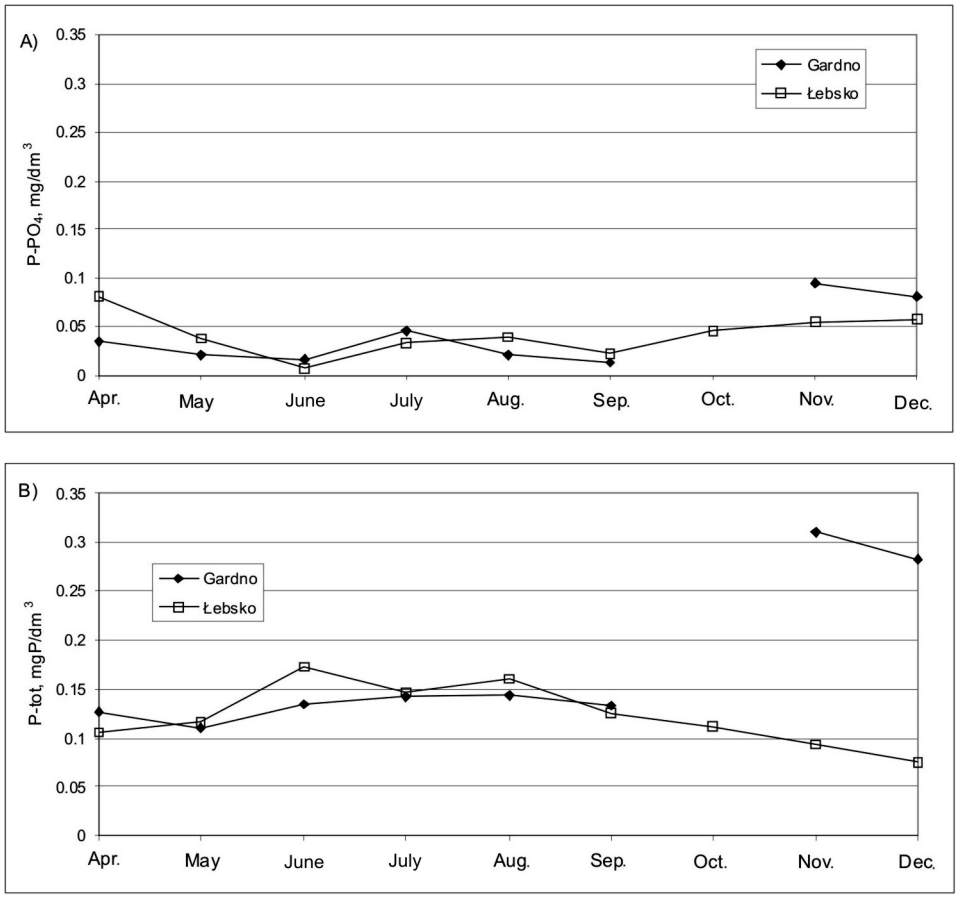

Fig. 4. Seasonal changes of phosphorus concentration (mgP/dm^3) in lakes Gardno and Łebsko, A) P-PO_4; B) P-total

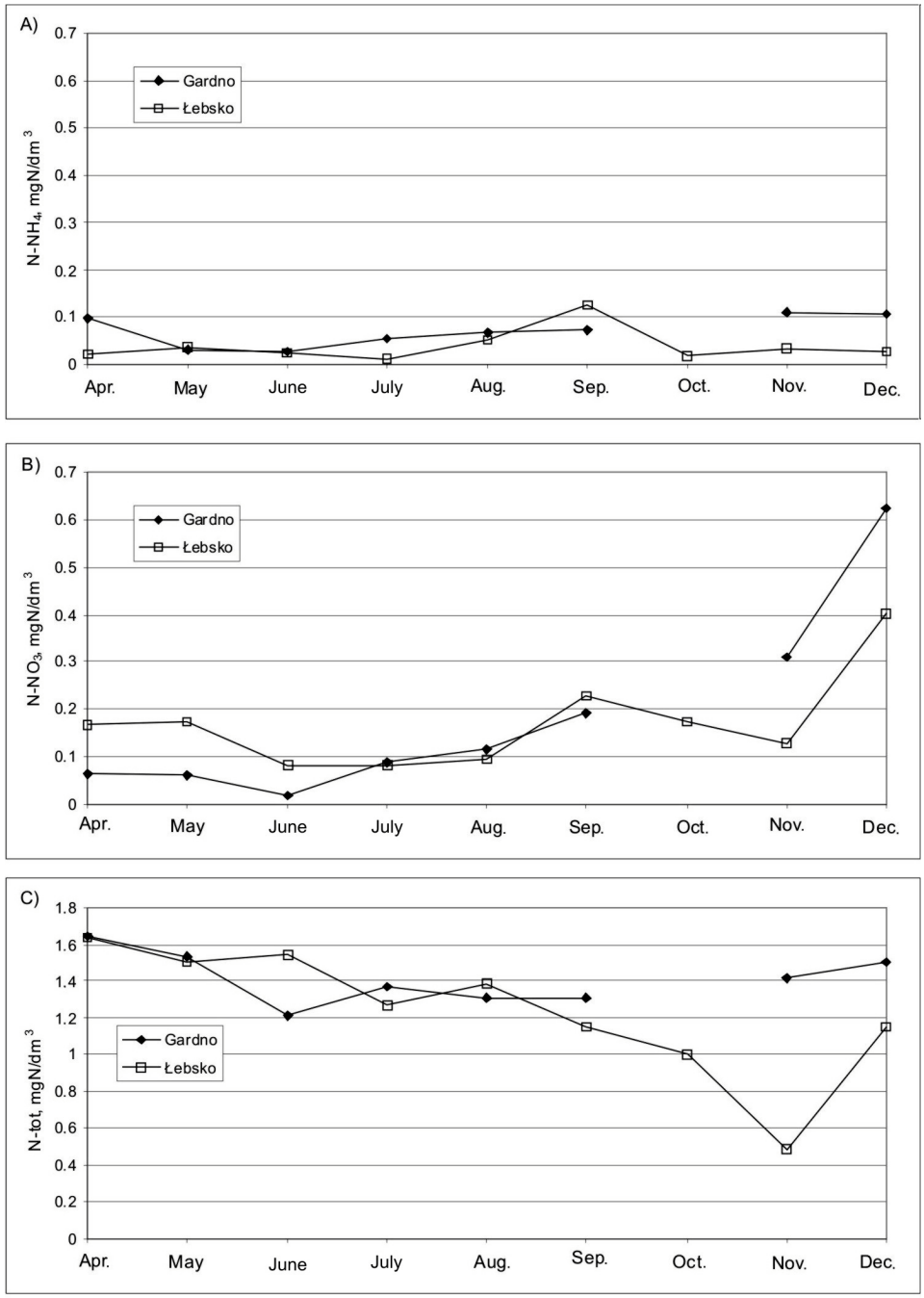

Fig. 5. Seasonal changes of nitrogen concentration (mgN/dm^3) in lakes Gardno and Łebsko, A) N-NH_4; B) N-NO_3; C) N-total

summer (about 15%) was observed. The same occurrence was find in the Łebsko Lake, but the summer increase was higher and more visible (Fig. 4b). The concentration of total phosphorus during vegetative season amounted about 0.15 mgP/dm^3, whereas the average for the spring/autumn/winter period was about 0.10 mgP/dm^3.
The organic phosphorus constituted variable part of total phosphorus, changing from 67% to 90% in the Gardno Lake and from 22% to above 80% in the Łebsko Lake. During the vegetative period amounts of organic phosphorus were the biggest and decreased in autumn-winter period.
During performed studies, ammonium concentration (Fig. 5a) was stable in both lakes and amounted to about 0.07 mgN/dm^3 (Gardno) and 0.04 mgN/dm^3 (Łebsko). Mean annual nitrate concentration was much higher and amounted to about 0.18mgN/dm^3 in Gardno and 0.17 mgN/dm^3 in Łebsko. NO_3-N concentration was higher in winter and early spring. The summer nitrates minimum in the Gardno Lake, similar to phosphates, was short-lived and observed in June (0.02 mgN/dm^3). In the case of the Łebsko Lake the decrease of NO_3-N concentration was long-term and went on from June to August, but the amount of nitrates was still high (0.1 mg/N dm^3), (Fig. 5b).
Mean annual total nitrogen concentration (Fig. 5c) in the Gardno Lake was about 1.4 mgN/dm^3, and in the Łebsko Lake it was about 1.3 mgN/dm^3. The nitrogen concentration was very stable in the first lake (only with the spring increase to 1.65 mgN/dm^3). More visible nitrogen changes were observed in the case of the Łebsko Lake. Similar to Gardno, the higher total nitrogen concentrations were observed in spring, while in the autumn the concentration of total nitrogen sharply decreased (it was not noted in Gardno). The lowest value – 0.48 mgN/dm^3 was measured in November.
Organic nitrogen was a dominant form of nitrogen throughout the whole study period, constituting from 60% to above 95% in both lakes (average 82%) of total nitrogen. Inorganic nitrogen concentration was the smallest during the growth season (about 8-9%), and its maximum attained in winter (about 40%). More important mineral form of nitrogen was nitrate-nitrogen.

DISCUSSION

The aim of this paper was the comparison of two lakes: Gardno and Łebsko. Performed measurements and analyzes showed that the lakes are similar. Mean annual concentrations of all measured biogens were approximate, however in the Gardno Lake higher then in the Łebsko Lake. Moreover, seasonal changes of the respective nitrogen and phosphorus forms content had similar course. The differences between lakes were statistically insignificant (Tab. 2). Statistical results showed, that only conductivity and salinity, directly connected with EC, indicates significant differences ($p = 0.025$) between Gardno and Łebsko lakes. In both cases the conductivity was high and changeable. This fact confirms that in favourable conditions the intrusions of salty water into the lakes occur, causing considerable increase in water salinity. This is especially visible in the case of the Łebsko Lake. On November 14,

Table 2

The mean annual value of analyzed parameters in lakes Gardno and Łebsko

Parameter	Lake				Significance*
	Gardno		Łebsko		
	mean annual value	SD	mean annual value	SD	
Conductivity, mS	1.74	0.826	2.87	1.06	Significant (0.025)
$P\text{-}PO_4$, mgP/dm^3	0.041	0.038	0.042	0.022	Non-sign (0.627)
P-tot, mgP/dm^3	0.176	0.076	0.124	0.033	Non-sign (0.192)
$N\text{-}NO_3$, mgN/dm^3	0.184	0.199	0.170	0.106	Non-sign (0.761)
$N\text{-}NH_4$, mgN/dm^3	0.071	0.032	0.041	0.035	Non-sign (0.114)
N-tot, mgN/dm^3	1.411	0.141	1.235	0.361	Non-sign (0.304)
N/P	9.09	3.29	10.55	3.66	Non-sign (0.304)

SD – standard division
* Results of t-test (5% significance level)

2007 the sea water content amounted to above 2.3‰, on the station without the direct influence of sea, whereas on the stations located near the Łeba Channel it was about 3‰ (Jarosiewicz and Ficek 2008). Moreover, the mean annual conductivity in Łebsko was over 60% higher than in the Gardno Lake. On the stronger influence of the Baltic Sea on the water quality in Łebsko indicate a domination of two ions: chlorides and sodium. The lake represents group 1 (chloride-sodium) according to Szczukariew classification (Cieśliński 2004). In the waters of Gardno a domination of four ions, i.e. calcium, chlorides, bicarbonates and sodium was observed (Cieśliński 2004).

Seasonal changes of nutrients concentration in lakes Gardno and Łebsko showed that the lakes are typical shallow lakes as defined by Scheffer (2001). In the case of phosphorus, it was not observed its systematic long time loss during the vegetative period, which is characteristic of stratified lakes (Wetzel 2001). In lakes Łebsko and Gardno the summer decrease of mineral phosphorus, in June, was short-time, and associated with the most intensive biological activity. During vegetative period phosphorus (mineral part) is rapidly incorporated into the biomass of planktonic algae and bacteria. At the same time (June) the maximum gross plankton primary production (GPP) was measured by Wielgat-Rychert and Rychert (2008). In the Gardno Lake GPP amounted to 3150 mgC m^{-2} d^{-1} and in the Łebsko Lake it was 3630 mgC m^{-2} d^{-1}. The intense sediment-water contact ensures that in the pelagic systems of shallow lakes, the mineral phosphorus losses associated with biological production are quickly supplemented.

Moreover, in vegetative season the total phosphorus concentration increased in both lakes about 15-50%. Good exposition to winds coupled with large surface area and average depth less than two meters result in constant circulation of water column and consequently in the intense sediment-water contact. As a result, a rapid return of most sedimentated material into the water column took place. In addition, the small average depths of Gardno and Łebsko lakes (Tab. 1) promote the temperature increase of lakes sediment, especially in summer. Higher sediment temperatures lead to an increase in mineralization rates, and consequently to an increased release of nutrients from the sediment. Measurements performed by Trojanowski (1990) showed that in case of Gardno and Łebsko, the concentration of P-total in sediments was the smallest in vegetative period. Moreover, high pH values (Fig. 3) associated with photosynthetic activity, reduce the capacity of iron to bind phosphorus and create good conditions to release the iron-bound phosphorus, accumulated in sediments. Because of significant phosphorus amounts in the sediments of Gardno and Łebsko, its supply to water column in favorable conditions can be intensive. Trojanowski (1990, 2003a) found, that, on average, the total phosphorus concentration in sediments of Gardno and Łebsko lakes amounted to about 0.16%.

The concentration changes of nitrogen were only to some extent similar to those of phosphorus. The differences between phosphorus and nitrogen seasonal changes are associated with three major features which differ nitrogen from phosphorus. Free nitrogen can be easily exchanged between the water phase and atmosphere (Wetzel 2001). In aquatic environment N_2 may be a product of denitrification and can disappear as gas in the atmosphere, but at the same time it can be incorporated into the organic matter by the N-fixing cyanobacteria. Moreover, the nitrogen exchange between sediments and water is less intensive then in case of phosphorus.

During summer, when total phosphorus concentration was increased, the concentration of N-total was stable from June to September, and lower than in spring. The spring increase of the N-total amounts in Gardno and Łebsko water column can be attributed to gaseous nitrogen fixation.

Lack of nitrogen concentration increase during summer was caused by less intensive reaction between sediments and water. Although sediments of lakes Gardno and Łebsko contain about 1.3% of nitrogen (Trojanowski 1990, 2003a), much of them can be immobilized and strongly sorbed to inorganic particles. It causes that the nitrogen diffusion rates are exceedingly slow. The nitrogen supply from sediments to the water column is associated with the organic matter decomposition.

Decomposition of organic material normally leads to the release of nitrogen as ammonium nitrogen, which can diffuse into the water column. In the water NH_4^+ is rapidly assimilated by algae and macrophytes or, in favourable conditions, transformed to nitrate. In case of lakes Gardno and Łebsko, the relatively stable concentration of NH_4-N was probably a result of both processes: organic matter decomposition increases the NH_4-N concentration and simultaneously assimilation and nitrification (in both lakes were good oxygen conditions) decreases the concentration. Intensive nitrification process caused that the concentration of NO_3-N in Gardno and Łebsko was about 2.5 times higher than NH_4-N concentration. Moreover, because nitrification and ammonium assimilation by algae were two competitive processes,

the decrease of assimilation rate (in winter) caused that the NO_3-N concentration was 6 times higher (in December) than NH_4-N concentration.
Performed measurements permit to determine a current trophy level of the Gardno Lake and the Łebsko Lake. According to Wetzel (2001) trophy of a lake refers to the rate at which organic matter is supplied by or to the lake per time unit. Productivity of lakes depends on many physical, chemical and biological parameters among which the concentration of biogens is very important factor. For the determination of the trophy of Gardno and Łebsko lakes, the classification proposed by Kajak (1983) and Hilbricht-Ilkowska (1989) was used. The classification covers the summer concentration of total nitrogen and phosphorus and summer ratio N:P. The amounts of phosphorus (P-tot) in both lakes, calculated as mean summer value (June – August) fall in the range of eutrophic lakes (eutrophy >0.10 mgP dm^{-3}). Similar, the summer ratio of total nitrogen to total phosphorus, which amounts in Gardno and Łebsko lakes to about 9, qualify these lakes as eutrophic. Simultaneously, the GPP values measured for both lakes during the growing season of 2007 (Wielgat-Rychert and Rychert 2008) classified the lakes as eutrophic – according to OECD classification – eutrophic >1000 mgC m^{-2} d^{-1} (Wetzel 2001). However, the comparison of present results with measurements performed in the 80s (Fig. 6) as part of surface water

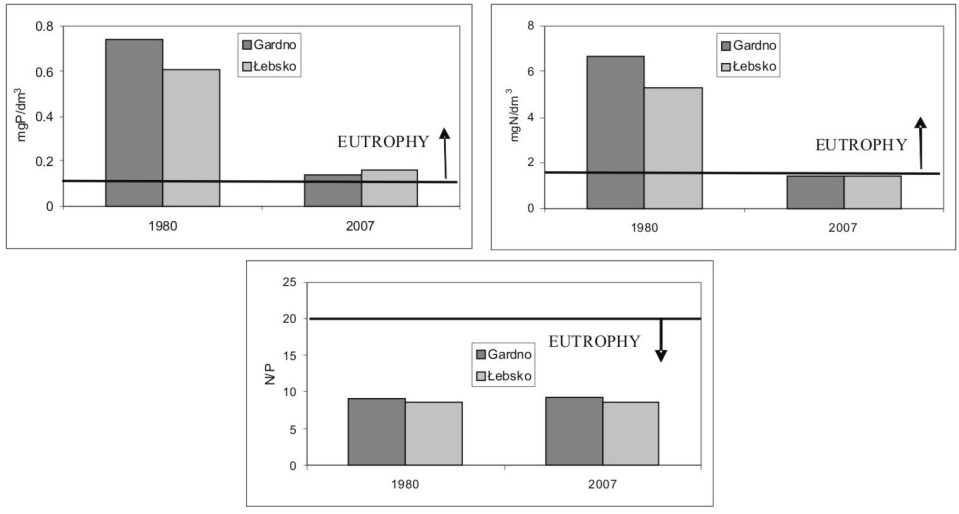

Fig. 6. Changes of some hydrochemical indices in lakes Gardno and Łebsko in years 1980 and 2007

monitoring programme (Cydzik and Soszka 1988) indicates a significant improvement of water quality in lakes. In case of the Gardno Lake the concentration of total nitrogen and phosphorus decreases 5-fold, and in Łebsko 4-fold. Data for comparison from 1980 were presented as average concentration value of total nitrogen and phosphorus in lakes, but even the smallest concentrations of nitrogen (in Gardno 3.5 mgN dm^{-3}; in Łebsko 3.2 mgN dm^{-3}) and phosphorus (in Gardno 0.3 mgP dm^{-3}; in Łebsko 0.4 mgP dm^{-3}) are about two times higher. The ratio N:P stays on the same

level. The improvement of the lakes quality is a result of several, overlapping factors related to the political and economic transformation in Poland. Much lower quantities of fertilizers applied and construction of a municipal wastewater treatment plant (Witek and Jarosiewicz, submitted) mean that loads from agriculture and from urban sources were reduced.

CONCLUSIONS

Performed measurements showed that both the concentration of biogens and seasonal nutrients changes were similar in lakes Gardno and Łebsko. Only conductivity and salinity indicated significant differences between these lakes.
High concentration of nitrogen and phosphorus qualify these lakes as eutrophic. Abundance of nutrients, supplemented in water column from sediments, present excellent conditions for phytoplankton growth, which intensive blooms were observed throughout all vegetative period in both lakes. But it is worth to underline that the quality of lakes was significantly improved during last 25 years. The concentration of biogens was over 4-fold decreased. This is very important information and desirable change trend, because both Gardno and Łebsko: (i) constitute part of the Slovinski National Park and (ii) are not degradation-resistant because of their unfavourable morphometric parameters.

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SEZONOWE ZMIANY STĘŻENIA SKŁADNIKÓW BIOGENICZNYCH DWÓCH PŁYTKICH JEZIOR PRZYMORSKICH GARDNA I ŁEBSKA; PORÓWNANIE

Streszczenie

Celem niniejszego opracowania była prezentacja i porównanie sezonowych zmian stężenia substancji biogenicznych oraz określenie poziomu trofii dwóch jezior przymorskich Gardna i Łebska. Jeziora te zlokalizowane są wzdłuż południowego wybrzeża Morza Bałtyckiego.

Zaprezentowane rezultaty są wynikiem badań prowadzonych od kwietnia do grudnia 2007 roku. Do celów publikacji na każdym z jezior wyselekcjonowane zostało jedno stanowisko pomiarowe, charakteryzujące się zarówno minimalnym oddziaływaniem słonych wód morskich, jak i słodkich wód rzecznych. Przeprowadzone analizy wykazały, iż dynamika składników biogenicznych w omawianych jeziorach jest podobna, a różnice stężenia poszczególnych form azotu i fosforu nie są istotne statystycznie. Ponadto zaobserwowano, że sezonowe zmiany stężenia biogenów w Gardnie i Łebsku mają przebieg typowy dla jezior płytkich. Określenie poziomu trofii jezior opierało się na porównaniu letnich stężeń azotu i fosforu całkowitego w toni wodnej jezior. Na podstawie tych porównań zarówno Łebsko, jak i Gardno zakwalifikowano do typu eutroficznego.