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INFLUENCE OF A MULTI-YEAR ARTIFICIAL AERATION OF A LAKE USING DESTRATIFICATION METHOD ON THE SEDIMENT-WATER PHOSPHORUS EXCHANGE

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WPŁYW WIELOLETNIEGO SZTUCZNEGO NAPOWIETRZANIA JEZIORA METODĄ DESTRATYFIKACYJNĄ NA WYMIANĘ FOSFORU POMIĘDZY OSADAMI A WODĄ

Badania prowadzono na małym (26,8 ha), lecz dość głębokim (17,3 m) Jeziorze Długim w Olsztynie. Przez ponad 20 lat jezioro było odbiornikiem ścieków, co doprowadziło do jego całkowitej degradacji. W latach 1987–2000 zbiornik był rekultywowany metodą sztucznego napowietrzania z destratyfikacją. Uzyskane wyniki badań pokazały, że sztuczne napowietrzanie skutecznie ogranicza zasilanie wewnętrzne. Zastosowanie tej metody rekultywacyjnej poskutkowało obniżeniem stężeń związków fosforu w badanych warstwach wód. Obniżenie zawartości fosforu ogólnego w osadach dennych (do poziomu 3–4 mg P g^{-1} s.m.) było prawdopodobnie związane z odłożeniem się nowej warstwy osadów, odzwierciedlającej zmienione przez rekultywację warunki środowiskowe w jeziorze. Badania przeprowadzone w latach kontrolnych pokazały, że zanotowane zmiany nie miały charakteru trwałego. Wysokie zawartości związków fosforu w osadach, niska pojemność sorpcyjna i tendencje do wyczerpywania tlenu w warstwach przydennych oznaczają, że możliwości dalszego obniżenia ilości związków fosforu w jeziorze za pomocą tej metody są ograniczone.

Summary

The research was conducted in a relatively small (26.8 ha) but quite deep (17.3 m) Lake Długie in Olsztyn, Poland. For over 20 years the lake was collecting sewage which eventually caused its complete degradation. In 1987–2000 the lake was restored using the artificial aeration method with destratification of water. The results showed that the artificial aeration effectively limited the internal loading. Application of this restoration method resulted in reduction of phosphorus compounds concentrations in the analyzed water strata. The decrease of TP in bottom sediments (to the level of 3–4 mg P g^{-1} DW) was probably associated with the fact that a new layer of sediments was created, reflecting a change in the aquatic conditions caused by the restoration. The investigations conducted in the reference years showed that the changes were not permanent. A high concentration of phosphorus compounds in bottom sediments, low sorptive capacity and a tendency to oxygen deficiency, indicate that further possibility to decrease the amount of phosphorus compounds in the lake by this restoration method is limited.

INTRODUCTION

Phosphorus is commonly regarded as the main factor determining water quality in lakes [35, 42, 44]. Most phosphorus is accumulated in bottom sediments. As Kajak reports [28], an only 10-cm top layer of the sediments contains 90–95% of phosphorus occurring in the whole ecosystem. Bottom sediments comprise not only a phosphorus store but in the permitting condition also an important source of this element for the primary producers. Although only a minor fraction of phosphorus found in the dissolved form in interstitial waters is released from bottom sediments [26, 37], it is regarded as the most frequent reason for delayed rejuvenation of a lake after reduction of the external loading [2, 35].

Regarding phosphorus compounds' release and inhibition in bottom sediments, their chemical composition is very important, especially the content of calcium, iron, aluminium and silica, silt minerals and organic matter [18, 19, 21, 39, 41, 45]. In natural conditions iron is an element that determines sorptive properties of bottom sediments. However, phosphorus bound to iron oxides or hydroxides is sensitive to changes in redox and pH conditions [3, 19, 33, 42]. It is also, in addition to loosely bound phosphorus, the most mobile fraction of sediment phosphorus [3, 14, 15, 29]. Its upkeep in sediments in the form of insoluble compounds, and thus limitation of its release to water, can be achieved by improved oxygenation of the near-bottom waters. Therefore, the most frequently used restoration method in lakes is artificial aeration [6, 7, 14, 30, 34, 47].

An example of lake restored for many years by artificial aeration method with destratification is the heavily degraded Lake Długie in Olsztyn. Considerable improvement of the aquatic conditions observed by Gawrońska and Lossow [11] and Grochowska and Gawrońska [20] confirmed that the applied method was effective in improving the trophic state in the lake. In the opinion of the aforementioned authors, it resulted from the internal loading reduction. Yet, an explanation is required for the decrease of phosphorus reduction rate in the water, observed in the following years, and the role of sediments in this process. This is the reason why the present investigations of the effect of the multi-year artificial aeration on phosphorus compounds' exchange across the sediment-water interface were carried out.

DESCRIPTION OF THE STUDY OBJECT

Lake Długie is situated in the western Olsztyn. It is a small (26.8 ha surface area) yet deep (17.3 m), elongated ($\lambda = 6.95$) reservoir, with a high penetration in the bed ($W_g = 0.3$) [24]. Lake Długie can be divided into three distinctive parts, differing by surface area, maximum depth and bottom profile (Fig. 1), and as a consequence, by the dynamics of water body and aquatic conditions [8, 36].

Lake Długie, as to its hydrology, is a closed reservoir, with no natural surface inflows and outflows. It is fed by surface run-off and underground waters. The lake also receives the storm waters from the nearby housing estate, and for over 20 years was collecting the untreated domestic waste water. Although in 1976 the input of the sanitary sewage was totally cut off, the lake remained heavily degraded and that is the reason why in 1987 its restoration was initiated, using the artificial aeration method.

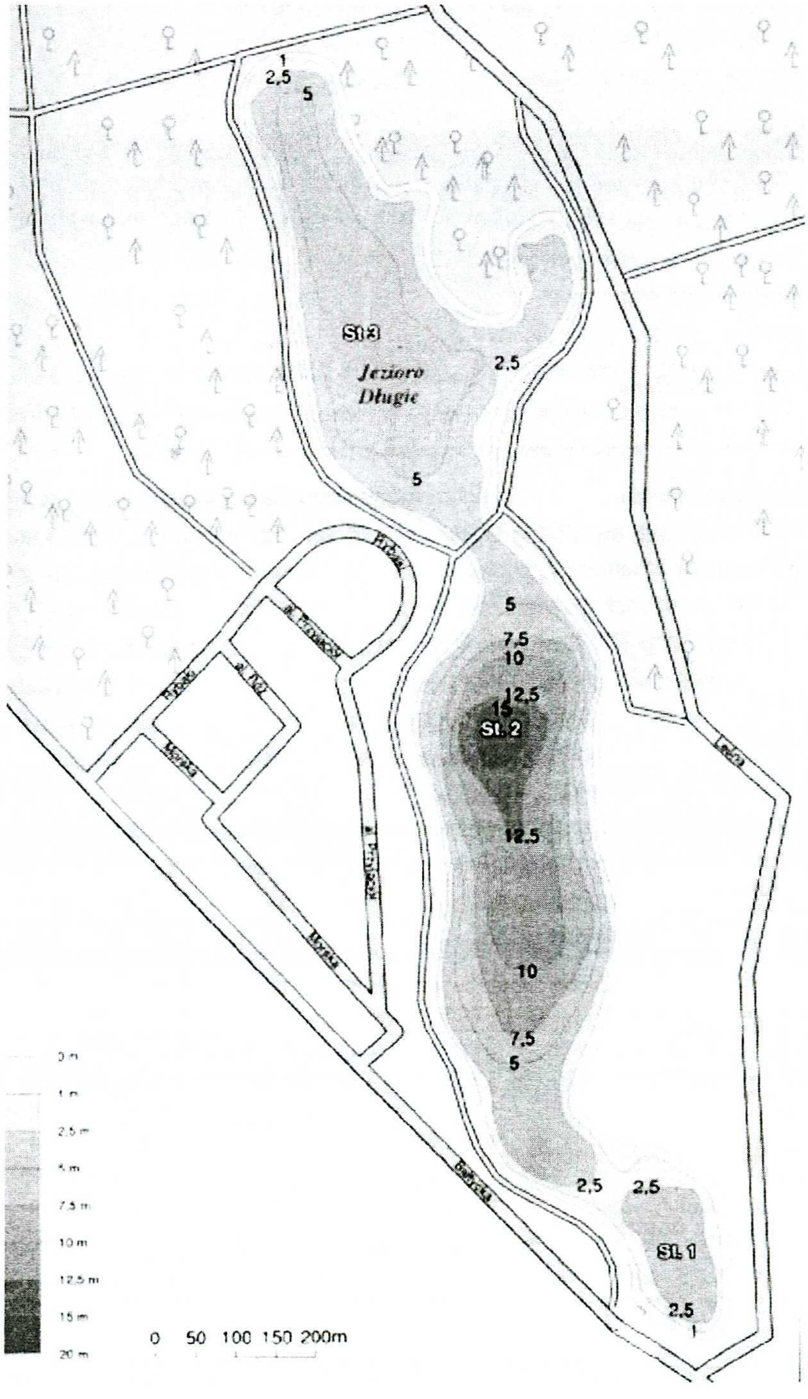

Fig. 1. Distribution of the bottom sediment examination stations in Lake Długie

MATERIAL AND METHODS

The restoration of Lake Długie by artificial aeration with destratification was conducted in 1987–2000, in two phases:

- phase I (July 1987 – April 1990) – using air-compressor of 150 m^3/h capacity and three „minifloks" aerators, located in the middle basin of the lake;
- phase II (August 1991 – November 2000) – using two air-compressors of 80 m^3/h capacity, operating in alternate mode, and two „minifloks" aerators, one situated in the middle basin and the other in the northern bay.

In order to determine the effectiveness of the restoration, in 1996 and 1999 aeration was terminated and the years were regarded as a reference.

The research on the multi-year aeration influence on the content and exchange of phosphorus compounds between sediments and water was conducted in annual cycles, throughout the restoration period. Samples of the near-bottom waters and the sediments were taken 8–9 times a year.

The samples of the near-bottom waters and the bottom sediments were taken with a Kajak's sampling tube on three stations (Fig. 1) located over the deepest spots in the distinguished lake basins:

- station 1 – in the non-aerated southern bay
- station 2 – in the middle basin, aerated since July 1987
- station 3 – in the northern bay, aerated since August 1991.

The near-bottom waters were obtained by decanting a 10-cm layer of water above the sediments. Non-disturbed, 10-cm thick cores of the bottom sediments were divided into two layers (0–5 cm and 5–10 cm). In order to separate the interstitial waters, samples of the sediments were centrifuged at 3,000 rpm for 20 min. The near-bottom and interstitial waters, after filtering through a paper filter, were subjected to chemical analyses. Determined were:

- phosphates (soluble reactive phosphorus – SRP) – by colorimetry with ammonium molybdate and tin(II) chloride as reducer (650 nm),
- total phosphorus (TP) – after mineralization with sulphuric acid and nitric acid, by colorimetry with ammonium molybdate and tin(II) chloride as reducer (650 nm),
- organic phosphorus (org. P) – computed as a difference between total phosphorus and phosphates,
- total iron – by colorimetry with 1.10-phenanthroline (512 nm).

The analyses were conducted according to the methods of Hermanowicz et al. [22]. Bottom sediments, after centrifugation of interstitial waters, were dried at room temperature and grinded into powder in a porcelain mortar. Amount of total phosphorus and the mineral fraction in the sediments were determined in accordance to the methods of Golachowska [16–18]. The content of organic matter, iron, aluminium and calcium in the sediments was determined by the methods of Januszkiewicz [25].

RESULTS

The restoration of Lake Długie by the method of artificial aeration has brought a considerable improvement in the aquatic conditions, displayed particularly in the near-bottom water layers.

Before the restoration, the limited dynamics of the water body in the deepest part of the lake was responsible for low and practically constant temperature of water near the bottom (4–6°C) (Fig. 2) which was additionally oxygen-deficient throughout the year. The artificial destratification eliminated thermal and chemical stratification in the lake. In effect, water temperature near the bottom increased by approximately 15–17°C and the oxygen conditions improved considerably (Fig. 2). In phase II of the restoration, the oxygen content in the near-bottom waters usually exceeded 5 mg O_2 dm^{-3} and only periodically in the middle of summer, in the middle basin it decreased to trace amounts.

Change in the aquatic conditions near the bottom during the restoration had much effect on phosphorus compounds content in the near-bottom waters, interstitial waters and sediments.

Data in Fig. 3 show that the near-bottom waters in Lake Długie were characterized by a high content of phosphorus compounds, varying throughout the research from 0.12 mg P dm^{-3} to 7.02 mg P dm^{-3}.

Before the restoration (1987), the highest quantities of TP were detected in the near-bottom waters, in the deepest middle basin (2.35 mg P dm^{-3} on average) while the lowest were measured in the northern bay (1.47 mg P dm^{-3} on average) (Tab. 1). The phosphates dominated over the year (approx. 68% TP) whereas organic phosphorus prevailed only in the summer.

Artificial aeration of the lake noticeably decreased the amount of phosphorus compounds in the examined water layers (Fig. 3), yet the changes ran differently on the individual stations. In phase I the decrease of TP was observed mainly in the middle basin while in phase II in both aerated basins (st. 2 and 3). In the last years of the restoration, the content of phosphorus compounds in the near-bottom waters of the examined basins was practically not higher than 1 mg P dm^{-3}, with the average of 0.5 mg P dm^{-3}. The smallest changes in total phosphorus amount were observed in the near-bottom waters of the non-aerated southern bay; thus its average content was twice higher than in the experimental basins (Fig. 3).

The decrease of phosphorus compounds amount observed in the near-bottom waters of the two aerated basins was caused mainly by the reduction of the mineral form. The concentration of phosphates, in comparison to the pre-restoration period, lowered by approximately 86% on st. 2 and by 68% on st. 3, while on st. 1 it remained practically unchanged.

The restoration of the lake resulted also in a reduction of organic phosphorus content in the examined water layer. However, in this case, it regarded all basins, and the content of organic phosphorus in the last year of the aeration comprised approximately 30% of the amount measured before the restoration (from 0.25 mg P dm^{-3} on st. 2 to 0.34 mg P dm^{-3} on st. 1, on average).

In the reference years (no aeration), the amount of phosphorus compounds in the near-bottom waters increased again, due to the growth of phosphate amount (Fig. 3). This increase of phosphates concentration was correlated with the advancing oxygen deficiency in the near-bottom waters. Nonetheless, the total quantity of TP was much lower than before the restoration (in 1996 by approx. 30% on st. 1 and 3 and by approx. 48% on st. 2) and, decreased with the aeration progress (in 1999 by approx. 50% on st. 1 and 3 and by approx. 60% on st. 2).

Much higher quantities of the phosphorus compounds were measured in the interstitial

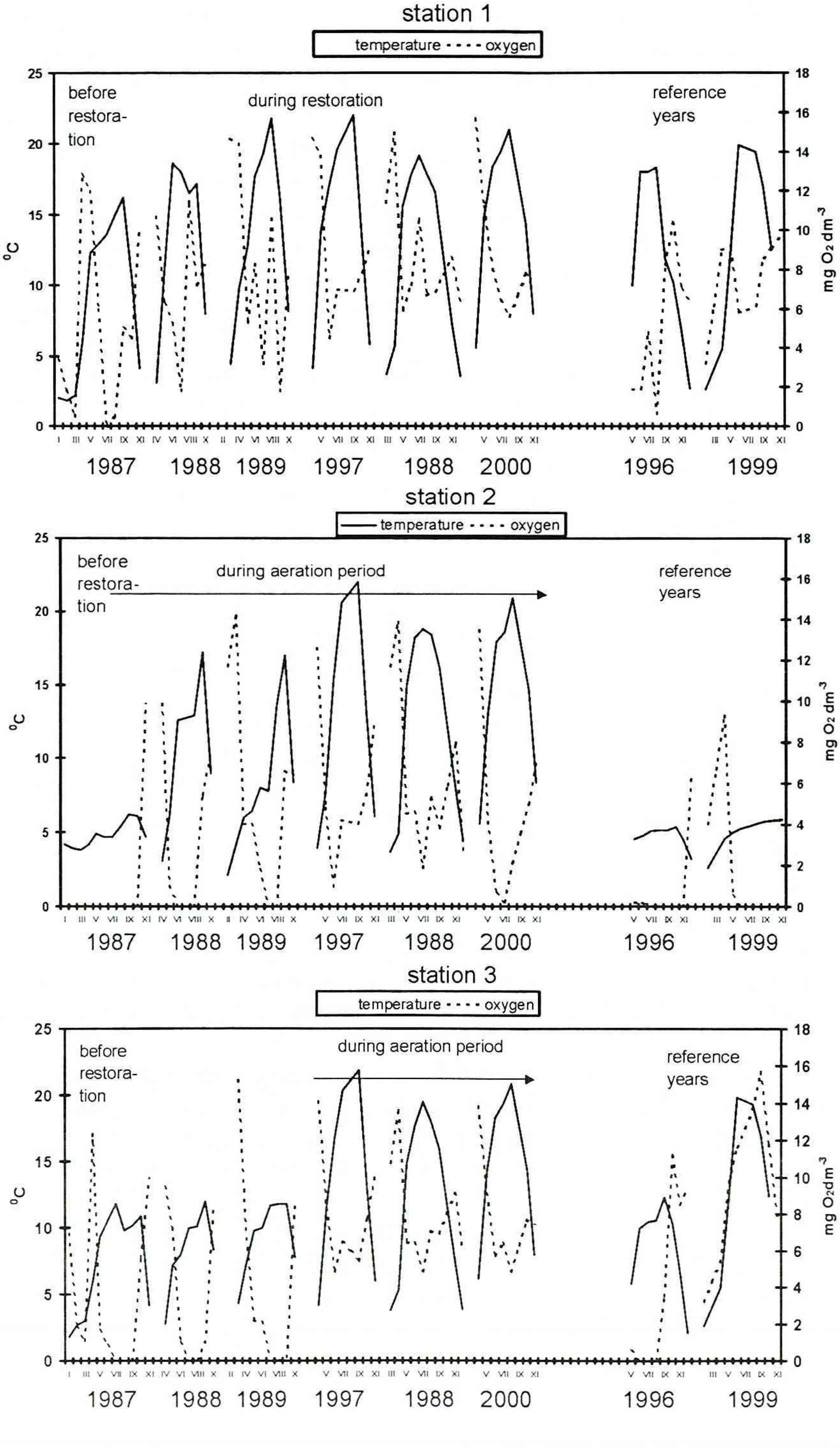

Fig. 2. Thermal and oxygen conditions in near-bottom water of Lake Długie

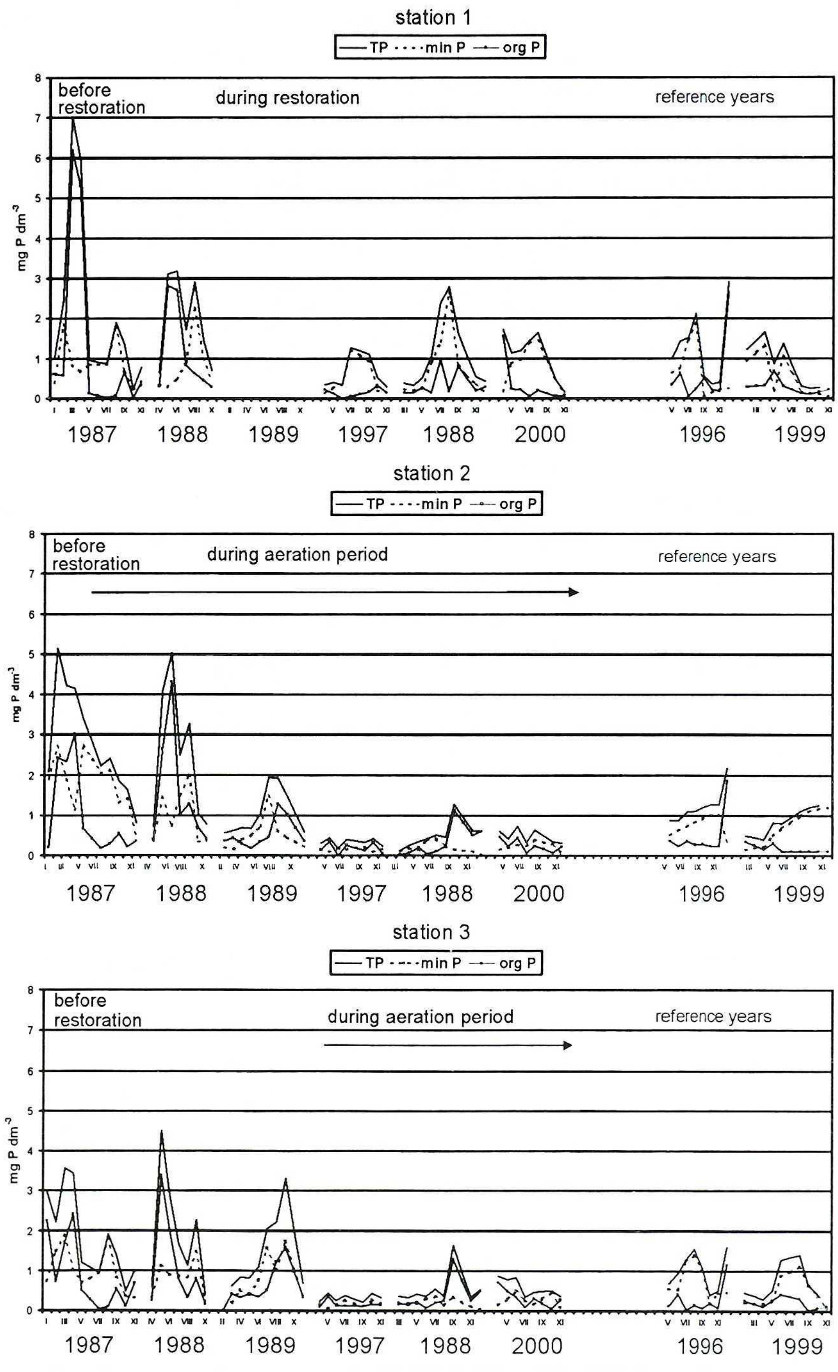

Fig. 3. Changes of mineral, organic and total phosphorus concentrations in near-bottom water of Lake Długie

waters. During the research they varied between 0.55 mg P dm^{-3} (0–5 cm layer) and 18.6 mg P dm^{-3} (5–10 cm layer); with phosphate as the dominant form (Fig. 4).

Before the start of the artificial aeration, the maximum amounts of TP in the interstitial waters, like in the near-bottom waters, were detected in the deepest, middle basin (Tab. 1).

Also in these waters, the artificial destratification caused an obvious reduction of the TP quantities as a result of the decrease of both examined forms i.e. phosphate and organic P (Fig. 4). In phase I of the restoration, this reduction was detected only in the middle basin and observed not until the second year of the aeration (1989) (Fig. 4); i.e., when the mean amount of TP decreased by approximately 50%.

In phase II of the restoration, a decrease of phosphorus compounds quantities was detected on all experimental stations (Tab. 1, Fig. 4). The maximum reduction was observed

Table 1. Mean amounts of total phosphorus in near-bottom water, interstitial water and bottom sediment of Lake Długie

Samples	Station	1987	1988	1989	1996*	1997	1998	1999*	2000
Near-bottom water (mg P dm^{-3})	1	1.72	1.95	–	1.28	0.61	1.21	0.79	1.11
	2	2.35	2.49	1.19	1.23	0.33	0.56	0.93	0.48
	3	1.47	1.92	1.57	1.00	0.32	0.57	0.72	0.59
Interstitial water (mg P dm^{-3})	Sediment layer 0–5 cm								
	Station	1987	1988	1989	1996*	1997	1998	1999*	2000
	1	4.48	4.96	–	2.47	2.29	3.54	3.16	3.26
	2	11.28	11.32	5.79	2.27	1.95	1.69	1.51	2.49
	3	6.40	5.75	5.40	2.84	1.92	2.29	2.22	2.01
	Sediment layer 5–10 cm								
	Station	1987	1988	1989	1996*	1997	1998	1999*	2000
	1	5.59	4.58	–	2.54	2.43	3.19	3.14	3.16
	2	12.21	11.98	5.82	2.71	3.25	2.85	2.27	3.17
	3	6.62	5.17	5.35	2.24	2.10	2.67	2.22	3.03
Bottom sediment (mg P g^{-1} DW)	Sediment layer 0–5 cm								
	Station	1987	1988	1989	1996*	1997	1998	1999*	2000
	1	3.57	3.69	–	3.40	3.40	3.29	3.23	3.38
	2	4.65	4.99	4.32	4.14	3.88	3.60	3.74	3.86
	3	3.99	3.28	3.47	3.50	3.22	3.24	3.10	2.92
	Sediment layer 5–10 cm								
	Station	1987	1988	1989	1996*	1997	1998	1999*	2000
	1	3.93	3.89	–	3.71	3.48	3.51	3.28	3.45
	2	4.93	4.73	4.38	3.93	3.86	3.70	3.54	3.61
	3	3.65	3.01	3.43	3.40	3.19	3.29	3.44	3.23

* – control years without aeration

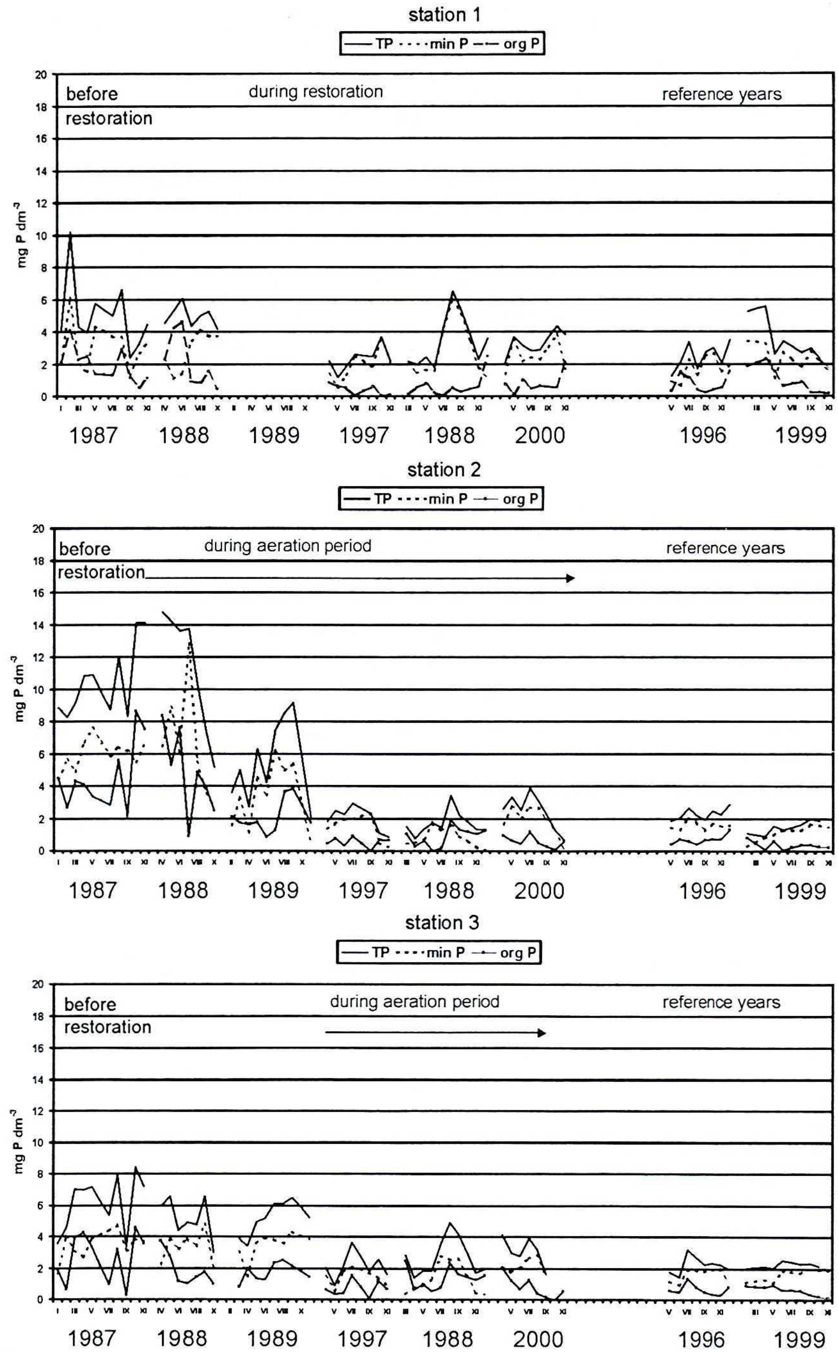

Fig. 4. Changes of mineral, organic and total phosphorus concentrations in the interstitial water of Lake Długie (sediment layer 0–5 cm)

in the longest aerated middle basin. Compared to the pre-restoration period, the mean TP amount decreased by approximately 76% in the waters of 0–5 cm layer and by 49% in the 5–10 cm layer. The smallest changes in TP quantity were measured in the non-aerated southern bay, and the reduction resulted from a decrease of the organic phosphorus amount.

Termination of the aeration brought no major changes to TP concentration in the interstitial waters. It remained on the level similar to the experimental years and in the case of the aerated basins, the amount even decreased a little.

The use of the lake as a reservoir receiving sanitary sewage and storm and the high degree of its pollution were reflected in the chemical composition of the bottom sediments: high quantity of organic matter and nutritive compounds and average (aluminium) or even low (iron, calcium) amount of the elements responsible for phosphorus inhibition in sediments [4].

The quantities of TP in the bottom sediments of Lake Długie during the survey were very high and varied in the range: 2.33 mg P g^{-1} DW – 6.03 mg P g^{-1} DW (Fig. 5). The higher amounts were usually detected in the deeper layers of the sediments. Phosphorus was deposited in the sediments mainly in the mineral form (70–90% TP).

Before the restoration, the majority of total phosphorus occurred in the sediments of the deepest middle basin (4.65 mg P g^{-1} DW on average in 0–5 cm layer and 4.93 mg P g^{-1} DW in 5–10 cm layer) (Tab. 1).

The artificial aeration of the lake clearly modified the quantity of phosphorus compounds in both examined sediment layers. In phase I of the aeration, the changes were relatively small. Nonetheless, a downward trend in the content of total phosphorus in the sediments of the middle basin was noted, with parallel significant oscillations in the northern bay and practically invariable amount in the southern bay (Fig. 5). In phase II of the restoration, a noticeable reduction of TP in the sediments was observed in both aerated basins, mainly as a result of the mineral form reduction (Fig. 5). At the same time, in the sediments of the non-aerated southern bay, despite considerable reduction of organic phosphorus, its total amount slightly increased.

Mineral fraction of phosphorus marked in the sediments was mainly bound to calcium, iron and aluminium. The per cent content of calcium-bound phosphorus was maximal: i.e., approximately 28% P min. on average in the sediments of the middle basin and the northern bay and 47% in the southern bay. The content of iron-bound phosphorus varied from 9% on st. 1 to 20% P min. on st. 2. The third fraction of phosphorus comprised the aluminium-bound phosphorus; i.e., approximately 10% in the sediments of the southern bay and 12% P min. in the sediments of the middle basin. The quantitatively smallest fraction of phosphorus was the labile phosphorus, loosely bound to sediments (approx. 1 to 2% P min.) (Fig. 6).

Comparison of the research results of the experimental and the reference years indicates that the artificial aeration caused changes mainly in the amount of iron-bound phosphorus and to a smaller degree of loosely bound phosphorus. In the reference years, when the near-bottom waters were oxygen-deficient in both experimental basins, contribution of the Fe-P fraction was clearly smaller while the amount of phosphorus loosely adsorbed to sediments increased (Fig. 6). Nonetheless, the direct relationship between iron amount in the sediments and the quantity of iron-bound phosphorus was not found.

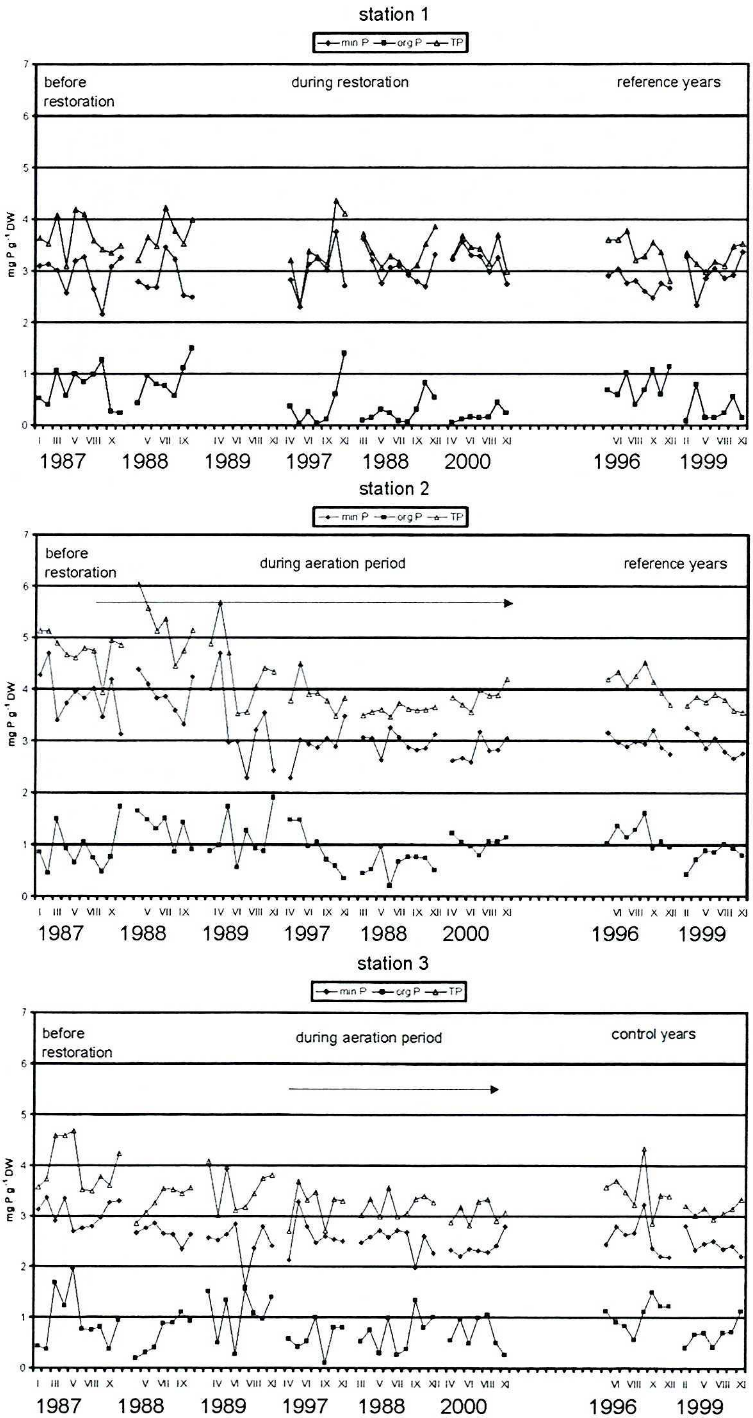

Fig. 5. Amounts of phosphorus forms in the bottom sediments of Lake Długie (sediment layer 0–5 cm)

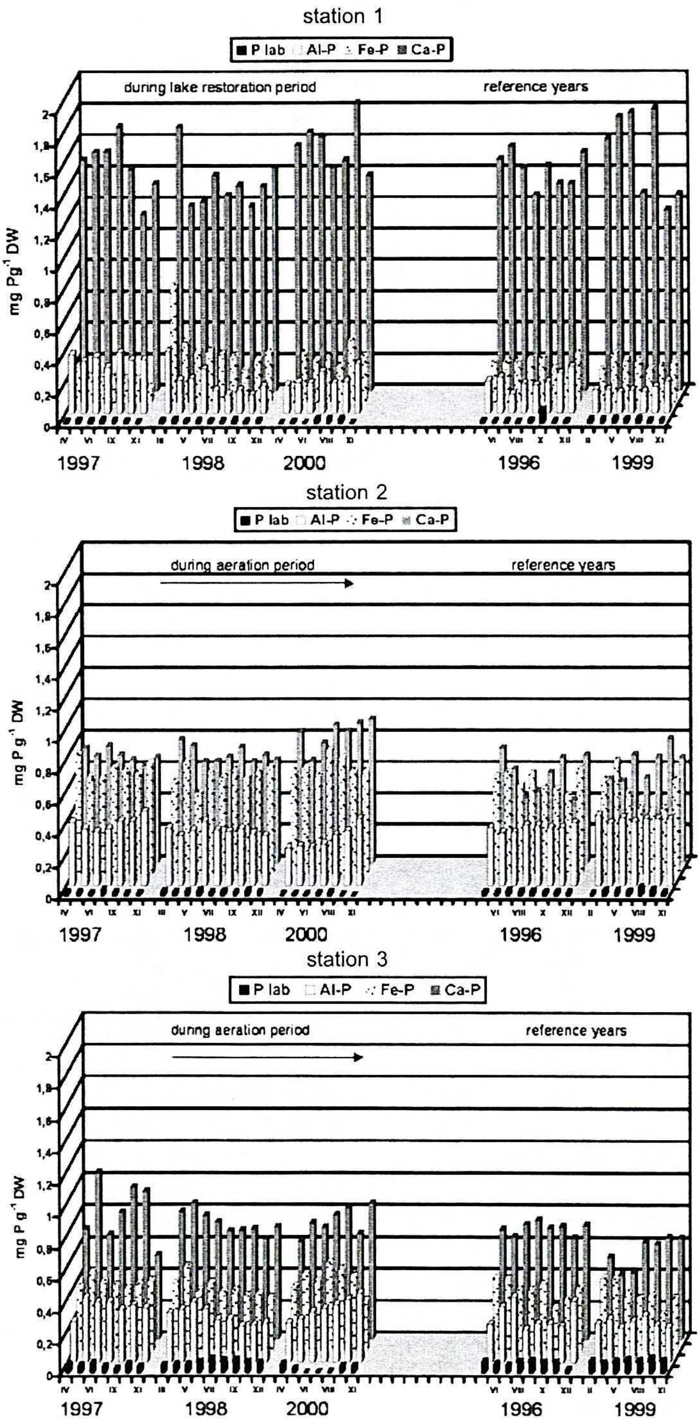

Fig. 6. Changes of phosphorus fractions amounts in the bottom sediments of Lake Długie

DISCUSSION

Lake Długie was one of many examples of the negative man's detrimental effects on urban lakes. Input of high loads of pollutants to a water reservoir with passive hydrological system and poor water mass dynamics, totally degraded this reservoir [8, 36]. In spite of the fact that the sewage input had been cut off, the lake remained heavily polluted [12, 13]. The lack of a noticeable improvement of the lake water's quality after external loading reduction is most often caused by internal loading. Nutrients deposited in bottom sediments can be released for years to water and keep up the primary production at a high level [2, 43, 45]. Such was undoubtedly the case of Lake Długie.

High quantities of phosphorus compounds in the sediments, with parallel total de-oxygenation of the near-bottom waters observed throughout the year [11, 13] and the subsequent decrease of the redox potential, resulted in releasing high amounts of this element from sediments to interstitial waters. Moreover, high amounts of hydrogen sulphur, occurring in reducing conditions, further limited sorptive potential of the sediments. Therefore, the quantities of phosphorus in the near-bottom waters and in the interstitial waters were very high, much higher than typically observed in eutrophic lakes [9, 14]. Restriction of the role bottom sediments play as a source of internal loading could be expected after oxygen conditions improvement in these waters, through artificial aeration of the lake. It has been confirmed not only by the reduction of phosphorus compounds quantity in the water body [20], but also (which was evidenced in this study) in the near-bottom and the interstitial waters.

Direct effect of the artificial aeration was displayed mainly by the amount of phosphates. Reduction of its quantity was observed only in both aerated basins while the amount in the non-aerated southern bay remained practically unchanged. The lower per cent reduction of this form of phosphorus in the interstitial waters, decreased as the sediments depth increased, and no doubt resulted from the limited direct impact of the applied restoration method on the bottom sediments. As observed by Gawrońska [14], the impact of oxygen conditions in the near-bottom waters on oxygen conditions and redox potential in the sediments, is restricted to the upper sediment layer (0–2 cm).

Quantitative changes in phosphates in the near-bottom waters in the conditions of complete destratification, can be an effect of its transport to water body, involvement in the production processes, precipitation in bottom sediments, or restriction of the release to water. In Lake Długie the last two processes, both directly dependent on the oxygen conditions played the main role [14, 35]. The evidence can be the decrease of phosphorus compounds' concentration not only in the water body [11, 20] but also in the interstitial waters of the experimental basins as well as higher than in the reference years amount of the iron-bound phosphorus fractions in the bottom sediments. The evidence for reduced release of phosphates from sediments to water as a result of the artificial aeration comprised first of all the results of the conducted laboratory examinations [5]. They show that the maximum values of the release from the sediments occurred in the non-aerated southern bay while the lowest values in the longest aerated middle basin.

The effect that redox conditions and decreased redox potential have on internal loading intensification, frequently emphasized by many authors [1, 2, 32, 38], was observable especially in phase I of the restoration and in the reference years when the near-bottom waters were totally deoxygenated. However, it should be mentioned that this increase was much smaller than before the restoration and decreased with the ongoing aeration.

Restoration of Lake Długie with the artificial aeration method also caused reduction of the organic phosphorus quantity. Unlike the case of phosphate, this reduction was observed in all lake basins, yet it was maximal in the longest aerated middle basin (by approx. 67% in the near-bottom waters and over 80% in the interstitial waters, compared to 1987). These changes could be the result of an intensification of the organic matter mineralization processes, caused by temperature elevation and oxygen conditions improvement. Taking into consideration that the decrease of organic phosphorus amounts was detected in the whole lake, the main reasons for such changes, as already reported by Gawrońska and Lossow [11] and Grochowska and Gawrońska [20], could be reduction of the primary production in the lake and improvement of the conditions for mineralization during settlement.

The diminishing rate of phosphorus compounds' reduction, observed in the following years of the restoration, and especially the relatively small, though clearly marked, increase of their concentrations in the analyzed waters in the last years of the aeration with parallel small decrease in the whole lake [20] seem to indicate no possibilities for further reduction of phosphorus compounds in the water.

Artificial aeration of the lake has caused considerable changes not only in the lake waters but also in the bottom sediments. However, the direction of these changes was variable and often difficult to explain. The reason was certainly the relatively small amount of phosphorus participating in the sediment-water exchange. According to Jørgensen [26] and Pettersson et al. [37], sediments released approximately 19–43% of total phosphorus occurring in interstitial waters in the dissolved form. This fraction however, constitutes only 1% of the sediment phosphorus [3].

As expected, a significant increase of TP in the sediments (from approx. 5 mg P g^{-1} DW to over 6 mg P g^{-1} DW) was observed only in phase I of the aeration. This increase was caused mainly by the increased amount of organic phosphorus (assumingly due to better settlement in the aerated environment) and not of mineral fractions of phosphorus as might be expected. However, in the following years of the experiment, the contents of both forms of phosphorus, mineral and organic, were reduced. The reasons of this unexpected phenomenon of total phosphorus amount reduction in the sediments, accompanied by a reduction in the whole lake, may be sought in the fact that a new layer of sediments was created, being a reflection of the modifications to the aquatic conditions in the lake caused by the multi-year restoration. As Shapiro et al. [40] and Kajak [27] report, in eutrophic lakes an increase of sediments can amount to 10–30 mm/year. Gächter and Wehrli [9] observed that due to compression, the annual increase of sediment layer diminishes. The same authors report that over 2 years, the 1.2-cm thick layer diminished to approximately 0.8 cm. Lake Długie was a hypertrophic lake with very high primary production, and during the 13 years that had passed since the aeration started, a layer thicker than the analyzed layer could have been created.

The conducted analyses revealed that the sorptive capacity of the bottom sediments in Lake Długie was rather low as displayed by no mineral phosphorus increase in the sediments and relatively small quantitative changes in the individual fractions.

The conducted examinations revealed, however, that the artificial aeration was in the first instance causing quantitative changes of the phosphorus fraction bound to iron. Still, the quantitative differences in this fraction observed in Lake Długie between the experimental and the reference years was rather small, which confirms the limited role of the phosphorus-iron cycle in phosphorus precipitation in water. The reason was undoubtedly the low Fe:P ratio in the near-bottom and the interstitial waters, usually equal to approximately 1:1 [4], whereas effective precipitation of phosphorus occurs at the ratio higher than 3:1 [32, 35, 46].

The conducted research showed that participation of mineral phosphorus bound to iron did not reflect the iron content in bottom sediments. Before the restoration, the quantities of iron contained in the bottom sediments of all basins were similar. In the restoration period, its participation in the total sediment dry weight noticeably increased, though mainly in the non-aerated southern bay and in the middle basin. The highest amounts of phosphorus bound to iron were detected in the sediments of the longest aerated middle basin (0.62 mg P g^{-1} DW on average) while the lowest amounts were found in the sediments of the non-aerated southern bay (0.26 mg P g^{-1} DW on average) [4]. Unexpectedly, low participation of Fe-P fraction in the non-aerated southern bay could be to some degree related to the higher reaction of waters in this lake section than in the other basins. This observation conforms to the hypotheses of some other authors [23, 46] that water reaction has an influence on phosphorus-iron complexes created in aerobic conditions. Moreover, as Lijklema reports [33], increase of reaction enhances desorption of phosphates, and the extra factor intensifying this process is the Fe:P ratio in the sediments. The higher the value, the higher desorption.

Many authors share the opinion [14, 15, 29, 37] that the most mobile fraction of mineral sediment phosphorus is labile phosphorus. During phase II of the restoration, the lower levels of labile phosphorus during aeration, as compared to the reference years, can indicate that restoration had a positive effect on the sediments (restricted conditions for phosphorus release). However, due to low participation, labile phosphorus had no effect on the quantity of phosphorus compounds in the lake waters.

In conclusion, artificial aeration of a lake with water destratification is an effective method for internal loading reduction. As a result, the quantities of phosphorus compounds are radically lowered not only in the near-bottom and the interstitial waters, but also in the water body. Improved oxygenation of waters, and especially limitation of phosphates availability to the autotrophs, diminishes the primary production in the lake, and consequently decreases the amount of organic phosphorus in both water and sediments. Although the research of the reference years have revealed that the changes in Lake Długie were not permanent, the measured reduction of nutrients release from sediments to water, lower concentrations of nutrients than before the restoration (decreasing in the following reference years), and changes in the chemical composition of bottom sediments, seem to indicate that the multi-year aeration can result in creating sediments that are in balance with the lake waters. This however, requires much longer restoration of the lake.

REFERENCES

[1] Auer M.T., N.A. Johnson, M.R. Penn, S.W. Effler: *Measurement and verification of rates of sediment phosphorus release for a hypereutrophic urban lake*, Hydrobiologia, **253**, 301–309 (1993).

[2] Boström B., J.M. Andersen, S. Fleischer, M. Jansson: *Exchange of phosphorus across the sediment – water interface*, Hydrobiologia, **170**, 229–244 (1988).

[3] Boström B., M. Jansson, C. Forsberg: *Phosphorus release from lake sediments*, Arch. Hydrobiol. Beih., **18**, 5–59 (1982).

[4] Brzozowska R.: *Wpływ wieloletniego sztucznego napowietrzania, na przykładzie Jeziora Długiego na wymianę związków biogennych między osadami a wodą*, rozprawa doktorska, UWM, Olsztyn 2004.

[5] Brzozowska R., H. Gawrońska, J. Grochowska, K. Lossow: *Nutrient release from the bottom sediments of the artificially aerated Lake Długie*, Limnological Review, **1**, 25–32 (2001).
[6] Bürgi H., P. Stadelmann: *Change of phytoplankton composition and biodiversity in Lake Sempach before and during restoration*, Hydrobiologia, **469**, 33–48 (2002)
[7] Cooke G.D., E.B. Welch, S.A. Peterson, P.R. Newroth: *Restoration and management of lakes and reservoirs*, Lewis Pub. (CRC Press Inc.). Boca Raton FL, 1993.
[8] Drozd H., K. Lossow, Cz. Mientki: *Chemizm wód Jeziora Długiego w Olsztynie*, Zesz. Nauk. ART Olsztyn, **9**, 17–28 (1979).
[9] Enell M., S. Löfgren: *Phosphorus in interstitial water: methods and dynamics*, Hydrobiologia, **170**, 103–132 (1988).
[10] Gächter R., B. Wehrli: *Ten years of artificial mixing and oxygenation; no effects on the internal phosphorus loading of two eutrophic lakes*, Environ. Sci. and Technol., **32**, 3659–3665 (1998).
[11] Gawrońska H., K. Lossow: *Possibilities of saprotrophic lake recultivation exemplified by Lake Długie in Olsztyn*, Polish Journal of Environmental Studies, **12**(3), 301–307 (2003).
[12] Gawrońska H., R. Brzozowska, J. Grochowska, K. Lossow: *Possibilities to reduce internal loading to lake water by artificial aeration*, Polish Journal of Environmental Studies, **12**(2), 171–179 (2003).
[13] Gawrońska H.: *Wpływ ograniczenia dopływu ścieków na warunki fizyczno-chemiczne wód Jeziora Długiego w Olsztynie*, Rocz. Nauk. Rol. H, **100**(4), 27–52 (1984).
[14] Gawrońska H.: *Wymiana fosforu i azotu pomiędzy osadami a wodą w jeziorze sztucznie napowietrzanym*, Acta Acad. Agricult. Tech. Olst. Protectio Aquarum et Piscatoria, **19**, 3–49 (1994).
[15] Golachowska J.: *Frakcjonowanie i oznaczanie mineralnych postaci fosforu w osadach dennych jezior*, Rocz. Nauk. Rol. H, **98**, 51–63 (1977).
[16] Golachowska J.: *Oznaczanie całkowitej zawartości fosforu mineralnego i organicznego w osadach dennych jezior*, Rocz. Nauk. Rol. H, **98**, 39–49 (1977).
[17] Golachowska J.: *Prosta i szybka metoda oznaczania fosforu w osadach dennych jezior*, Rocz. Nauk. Rol. H, **98**, 27–37 (1977).
[18] Golterman H.L.: *The distribution of phosphate over iron-bound and calcium-bound phosphate in stratified sediments*, Hydrobiologia, **364**, 75–81 (1998).
[19] Gomez E., C. Durillon, G. Rofes, B. Picot: *Phosphate adsorption and release from sediment of brackish lagoons: pH, O_2 and loading influence*, Wat. Res., **33** (10), 2437–2447 (1999).
[20] Grochowska J., H. Gawrońska: *Restoration effectiveness of a degraded Lake using multi-year artificial aeration*, Polish Journal of Environmental Studies, **13**(6), 671–681 (2004).
[21] Hartikainen H., M. Pitkänen, T. Kairesalo, L. Tuominen: *Co-occurrence and potential chemical competition of phosphorus and silicon in lake sediment*, Wat. Res., **30**(10), 2472–2478 (1996).
[22] Hermanowicz W., W. Dożańska, J. Dojlido, B. Koziorowski, J. Zerbe: *Fizyczno-chemiczne badanie wody i ścieków*, Arkady, Warszawa 1999.
[23] Holtan H., L. Kamp-Nielsen, A.O. Stuanes: *Phosphorus in soil, water and sediment: an overview*, Hydrobiologia, **170**, 19–34 (1988).
[24] IRŚ Olsztyn: *Mapa batymetryczna i dane morfometryczne Jeziora Długiego w Olsztynie*, 1958.
[25] Januszkiewicz T.: *Studia nad metodą analizy współczesnych osadów dennych jezior*, Zesz. Nauk. ART Olsztyn, **187**(8), 3–30 (1978).
[26] Jørgensen S.E.: *The influence of phosphate and nitrogen in sediment on restoration of lakes*, [in:] Symposium on Interaction between sediments and water, Amsterdam 1976, 387–389.
[27] Kajak Z.: *Eutrofizacja jezior*, PWN, Warszawa 1979.
[28] Kajak Z.: *Hydrobiologia – limnologia. Ekosystemy wód śródlądowych*, PWN, Warszawa 2001.
[29] Kentzer A.: *Fosfor i jego biologicznie dostępne frakcje w osadach jezior o różnej trofii*, Wydawnictwo UMK, Toruń 2001, 1–111.
[30] Klapper H.: *Technologies for lake restoration*, J. Limnol., **62**(1), 73–90 (2003).
[31] Koski-Vähälä J., H. Hartikainen, P. Tallberg: *Phosphorus mobilization from various sediments pools in response to increased pH and silicate concentration*, J. Environ. Qual., **30**, 546–552 (2001).
[32] Lijklema L.: *Internal loading – mechanisms and assessment of magnitude*, [in:] Lake Pollution and Recovery. European Water Pollution Control Association, Rome 1985, 181–189.
[33] Lijklema L.: *Phosphorus accumulation in sediments and internal loading*, Hydrobiological Bulletin, **20** (1/2), 213–224 (1986).
[34] Lossow K.: *Wpływ sztucznej destratyfikacji na układy fizyko-chemiczne wód Jeziora Starodworskiego*,

Zesz. Nauk. ART Olsztyn, **11**, 3–64 (1980).

[35] Marsden M.W.: *Lake restoration by reducing external phosphorus loading: the influence of sediment phosphorus release*, Freshwater Biology, **21**, 139–162 (1989).

[36] Mientki Cz., H. Drozd, K. Lossow: *Związki azotu i fosforu w Jeziorze Długim w Olszynie*, Zesz. Nauk. ART. Olsztyn, **9**, 31–45 (1979).

[37] Pettersson K., B. Boström, O.-S. Jacobsen: *Phosphorus in sediments – speciation and analysis*, Hydrobiologia, **170**, 91–101 (1988).

[38] Sandman O., K. Eskonen, A. Liehu: *The eutrophication history of Lake Särkinen, Finland, and the effects of lake aeration*, Hydrobiologia, **214**, 191–199 (1990).

[39] Sarazin G., J.F. Gaillard, L. Philippe, Ch. Rabouille: *Organic matter mineralization in the pore water of a eutrophic lake (Aydat Lake, Puy de Dôme, France)*, Hydrobiologia, **315**, 95–118 (1995).

[40] Shapiro J., W.T. Edmondson, D.E. Allison: *Changes in the chemical composition of sediments of Lake Washington 1958–1970*, Limnol. Oceanogr., **16**(2), 437–452 (1971).

[41] Søndergaard M., J. Windolf, E. Jeppesen: *Phosphorus fractions and profiles in the sediment of shallow Danish lakes as related to phosphorus load, sediment composition and lake chemistry*, Wat. Res., **30** (4), 992–1002 (1996).

[42] Søndergaard M., J.P. Jensen., E. Jeppesen: *Role of sediment and internal loading of phosphorus in shallow lakes*, Hydrobiologia, **506–509**, 135–145 (2003).

[43] Søndergaard M., J.P. Jensen, E. Jeppesen: *Internal phosphorus loading in shallow Danish lake*, Hydrobiologia, **408/409**, 145–152 (1999).

[44] Vollenweider R.A.: *Advances in defining critical level of phosphorus in lake eutrophication*, Mem. Ist. Ital. Idrobiol., **33**, 53–83 (1976).

[45] Wiśniewski R.J.: *Rola zasilania wewnętrznego w eutrofizacji zbiorników zaporowych*, Bibl. Monit. Środ., Łódź 1995, 61–70.

[46] Wiśniewski R., D. Kopeć, J. Kopeć: *Optimization of phosphate inactivation process with ferric chloride in Lake Łasińskie sediments*, Limnological Review, **3**, 261–268 (2003).

[47] Woo-Myung H., K. Bomchul: *The effect of artificial destratification on phytoplankton in a reservoir*, Hydrobiologia, **524**, 229–239 (2004).

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