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Original Research

Restoration Effectiveness of a Degraded Lake Using Multi-Year Artificial Aeration

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Abstract

Lake Długie in Olsztyn, Poland, received untreated sewage for over 20 years from a housing estate which probably caused its complete degradation. The lake was regarded in the 1970s as one of the most polluted in Poland; its chemical composition was similar to that of diluted sewage. After the sewage diversion, the amount of organic compounds and nutrients in the water diminished, although the aquatic environment conditions did not improve considerably. Improvement of the trophic state of the lake might have been expected only after applying a relevant restoration technique.

Our paper presents the results from a study of the effectiveness of a multi-year restoration of Lake Długie, using the artificial aeration method with destratification. Analysis of the obtained results supports the conclusion that the more than 10-year artificial circulation has resulted in a radical improvement of the environmental conditions in the lake displayed by: increase of oxygen content in the whole water volume, reduction of its consumption rate during both stagnation periods, shortening of the anoxia period in the near-bottom waters, and increase of the redox potential. The artificial aeration has caused a radical decrease of nutrients and organic compounds content in the water, and eventually improved the trophic state. Concentration of phosphorus compounds in the water was reduced mainly due to halted release of the phosphate phosphorus from the bottom sediments. In the case of nitrogen compounds, halted release from the bottom sediments, intensification of the nitrification processes but mainly due to the denitrification process. Despite the considerable reduction of nitrogen and phosphorus compound concentrations in the lake waters, the applied treatment has not resulted in sufficient reduction of the nutrients as to limit the primary production. The lake had remained a heavily eutrophic reservoir which was confirmed by still high values of BOD_5, chlorophyll a and low transparency measured by Secchi disk. In the following years of artificial aeration a drop in the reduction rate of the phosphorus compound concentrations was observed which at the parallel lack of iron and manganese in the water indicates that in the case of Lake Długie the capacity for further improvement of its trophic condition in this way had been practically exhausted. Better effects may be expected only after the application of a supportive method, consisting of phosphorus precipitation and fixing in the bottom sediments.

Keywords: restoration, artificial aeration, destratification, internal loading, phosphorus, nitrogen

Introduction

In heavily degraded lakes in which the main source of nutrients comprise the bottom sediments, reduction of the external load does not improve the environmental conditions [1, 2].

Many authors [3, 4, 5] share the opinion that in such reservoirs a specific restoration technique must be implemented which enables limitation of the nutrient concentration in the water circulation, either through removal from the lake ecosystem or through deposition and permanent fixing in the bottom deposits.

Nutrients can be trapped in the sediments as a result of the redox potential increase. Due to the fact that the

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redox potential value is determined mainly by oxygen content in the near-bottom waters, the most frequently applied restoration technique is artificial aeration [6, 7, 8]. Such treatment can be performed without destruction of the thermal stratification in a lake (hypolimnetic aeration) or with thermal destratification (artificial circulation).

The great majority of the artificially-aerated lakes in Poland and in the world has been restored with the destratification method [3, 9, 10].

Despite the popularity of the artificial circulation method, only the results of short-term (mostly 2- to 3-year) restoration trials with this method are known. Still, there is no answer to the question of whether through artificially achieved actuation of water masses, the trophic state of degraded lakes can be permanently improved. In other words: whether after the compressors have been switched down, the modified aquatic conditions in the lake will be sustained.

The aim of the present study was to determine the effectiveness of Lake Długie restoration with the method of multi-year artificial aeration with destratification, and to find out whether the method can be applied to restoring degraded lakes.

The aim has been achieved by the following:

- analysis of the environmental conditions in the lake before restoration, on the basis of results from 1984.
- analysis of the physico-chemical settings in the lake during artificial aeration, on the basis of results from the selected years of 1987, 1989, 1992, 1998, 2000.
- analysis of the physico-chemical settings in the lake after disconnection of the artificial aeration (reference years), on the basis of the results from the years 1996 and 1999.

Methods

Lake Długie is situated on the western side of Olsztyn. The lake's surface area equals 26.8 ha. The reservoir has an elongated shape (Fig. 1). Its maximum length (1760 m) related to small width (240 m) makes elongation of 6.9. The lake bowl is distinctly divided into three sections: shallow (3 m) and small (2.3 ha) southern bay, the deepest (17.3 m) and largest (13.4 ha) middle section, and finally the northern section separated with a shallowness and bridge of maximum depth 5 m and 11.1 ha surface area. Lake bowl volume amounts to 1,415,000 m^3. It has no natural surface outflows and inflows.

Principle of the Experiment

The destratification of Lake Długie waters was performed with the help of the "minifloks" aerators fed with air generated by air-compressors housed in a compression station located on the east shore [11].

The lake's restoration with the artificial aeration method was carried out in two phases:

Phase I – July 1987 through April 1990. Three "minifloks" aerators were applied, placed on three spots of the middle basin (at depths of 5, 10 and 17 m) and an air-compressor with about 150 m^3/h delivery.

Aeration was performed continuously from January to October. The system was defective from the beginning of its operation [11] due to non-uniform air delivery and repeated breaks of the PCV pipes. The installed aerators were too short (by 5 metres) for the deepest water layers to be aerated.

Phase II – 12 August 1991 through November 2000. The artificial aeration of the lake was performed in accordance with the new conditions. Two air-compressors (operating in alternate mode) were applied with about 80 m^3/h delivery and two "minifloks" aerators.

The first aerator, 10 m long, was placed over the deepest spot in the lake in such way that the bottom opening was situated 1 m above the bottom and the top opening under the water surface; the second aerator, 5 m long, was placed in the northern bay. Compressed air was delivered to the aerators by rubber pressure pipes. The artificial aeration was carried out under strictly controlled conditions which enabled adjustment of the aeration time to the present environmental conditions in the lake and disconnection of the air-compressor during autumn turnover and periodically in winter. As a result, considerable saving of electric energy was obtained.

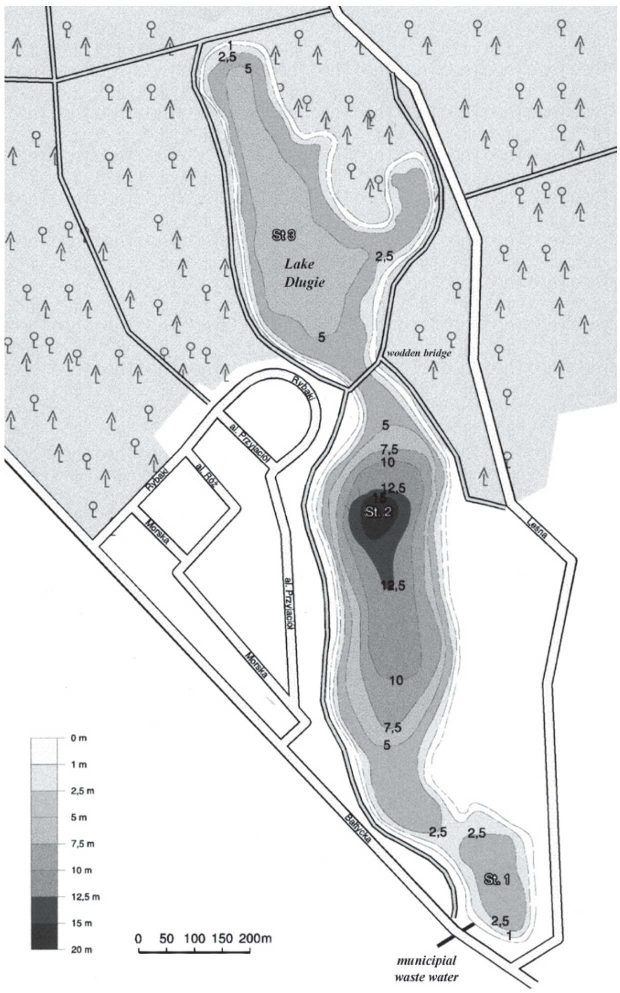

Fig. 1. Bathymetric map of Lake Długie.

Physico-Chemical Analyses of Water

The physico-chemical analyses of the lake waters were conducted in annual cycles, with average sampling frequency once per month.

Water for chemical analyses was sampled from three experimental stations located over the deepest spot of the three selected basins in Lake Długie (Fig. 1):

station 1 - in the non-aerated southern bay, from a depth of 1 m,

station 2 - in the middle part, aerated since July 1987, from a depths of 1, 5, 10 and 15 m,

station 3 - in the northern bay, aerated since August 1991, from a depth of 1 and 5 m.

On each station the thermal and oxygen profile was performed at every 1 m of depth.

Water sampling was done with a 5-litre Ruttner apparatus, and transparency was measured by the Secchi disc.

Chemical analyses of the water were conducted according to standard methods [12].

Results

Thermal Conditions

Before restoration, the worst mixing conditions were in the middle basin of the lake (station 2), classified as bradymictic lake [13]. Poor water mass dynamics were displayed by the lack of profound spring turnover, a fast-setting and stable thermal stratification in summer, usually with a 2–3 m epilimnion, a sharp thermocline and cold and thermally-uniform hypolimnion (Figure 2), and late (end of November) and short autumn turnover.

The northern bay (station 3) was also characterized by restricted water dynamics. Its small depth enabled full homothermy in spring and autumn; however, due to the lake's shielding by high elevations grown with forest, the summer stratification was setting up very fast with a shallow (2–3 m) and warm epilimnion and a sharp thermocline laid on the bottom (max. gradient amounted to 5.3ºC/m).

The best water mixing conditions were determined in the southern bay (station 1), although here also periodic thermal stratification was observed. Between 2 and 3 m depth a temperature jump was measured with up to 4.0ºC/m gradient.

Artificial aeration of the lake, initiated in July 1987 (Phase I) had an effect on the thermal settings only in the middle basin. The observed changes were minor and limited to the epilimnion deepening (to 5 m depth) and small temperature rise of the near-bottom waters (by about 2ºC) (Fig. 2). Nonetheless, it enabled a profound autumn turnover.

In the following years of Phase I of the experiment, complete homothermy was determined in the winter months and in the early spring. However, in summer complete destratification was observed only down to 13 m. Although the deepest water layers were not mixed, a clear temperature rise (up to 13.6ºC) was detected and the complete autumn turnover was noted already in September at 17.0ºC (Fig. 2).

In Phase II of the restoration when the middle basin and the northern bay were artificially aerated, full thermal equilibrium in the water was observed (Fig. 2). The maximum temperature of the near-bottom layers amounted to 20.0-22.0ºC. Its minor differences between the surface and the bottom (in the range of 1.0-4.0ºC) were noted only in spring or in peak of summer stagnation, at the rapid growth of the air temperatures (Fig. 2).

Disconnection of the artificial aeration in the reference years stimulated a return to the typical thermal settings in Lake Długie, observed before the restoration (Fig. 2).

Oxygen Conditions

Before restoration only the surface layers were characterized by high oxygenation (often above 150% saturation).

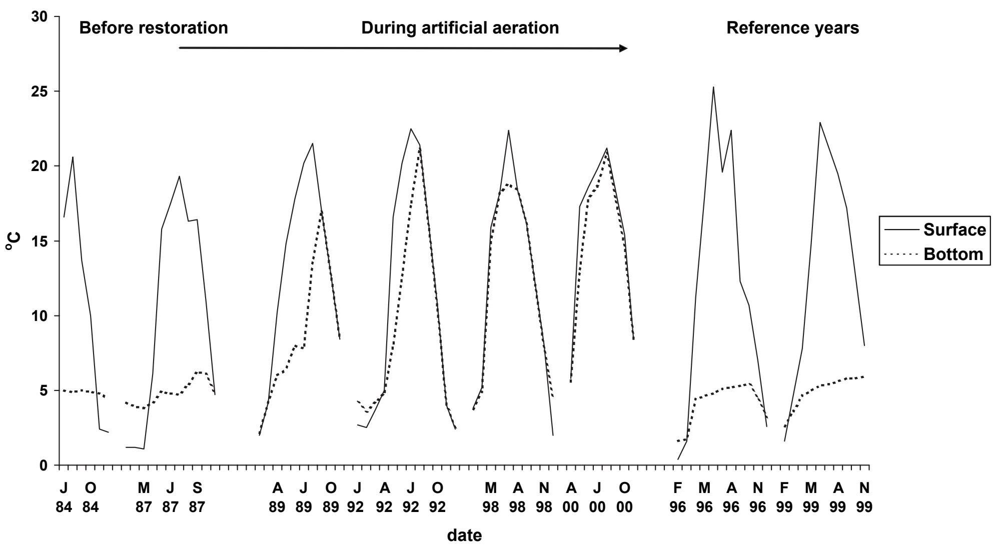

Fig. 2. Temperature changes in the surface and near - bottom waters in Lake Długie in various years (station 2).

Already between the first and the second meter of depth at all stations a sharp oxycline was present causing full oxygen depletion at a water depth below 4 m. In autumn 1986 H_2S was detected at a water depth below 13 m [11].

Start-up of the artificial aeration in July 1987, at the present stable thermal stratification, did not cause any considerable changes of lake water oxygenation. The changes were confined to the middle section only, where the range of layers containing oxygen deepened to about 6 m, with simultaneous reduction of the oxygen concentration in the surface waters (Fig. 3). In the subsequent years of Phase I of the restoration, the water of the deep central basin were artificially mixed and oxygenated down to 12 m depth; however, deeper, the oxygen content was decreasing from spring (about 1.0 mg O_2/l) to full oxygen depletion in the summer.

Much better effects were obtained in Phase II of the aeration. The oxygen content in surface water varied in a wide range (from 3.0 mg O_2/l to 17.0 mg O_2/l), whereas in the near-bottom layers it usually did not exceed 2.0 mg O_2/l and would drop to 0.5 mg O_2/l only periodically (Fig. 3). In the shallow waters of the northern bay the oxygen content was levelled in the water column and practically did not fall below 5.0 mg O_2/l.

Disconnection of the artificial aeration in the reference years was causing repeated deterioration of the deeper water's oxygenation. The oxygen settings at the end of summer stagnation were similar to those observed in the lake before the restoration. However, the rate of oxygen depletion was much slower (full deoxidization was observed only in the beginning of July). The range of deoxidized layers also diminished (maximum to 10 m under the water table).

Phosphorus Compounds

The domestic sewage discharged to Lake Długie were responsible for the fact that, a few years later after its diversion, the waters of this reservoir were characterized by still very high concentrations of the phosphorus compounds (the content of total phosphorus amounted up to 3.5 mg P/l) present mainly in the form of phosphates. An obvious vertical stratification was observed for total phosphorus displayed by an increase of its value along with the depth.

Before restoration, the lowest concentrations, irrespective of the examination station's location, were measured in the surface waters (from 0.092 to 0.475 mg P/l), (Fig. 4), whereas the highest near the bottom in the middle basin (from 2.64 to 3.45 mg P/l) (Fig. 5).

The applied restoration technique has caused reduction of the total amount of phosphorus compounds in the lake (mainly due to the decrease of the mineral P fraction in the deeper layers, mainly in the near-bottom waters). During aeration its concentrations were levelled in the whole water volume and in 2000 they practically did not exceed 0.25 mg P/l (Figs. 4, 5).

In the reference years, the content of phosphorus in the lake increased again, which was caused by an increase of the organic P concentration in the surface layers, and to a smaller degree by an increase of the phosphate amounts near the bottom.

Nitrogen Compounds

Before restoration, the waters of Lake Długie were characterized by very high concentrations of total nitrogen: 1.5 to 26.0 mg N/l (Figs. 6, 7). Particularly high amounts of the nitrogen compounds were present in the near-bottom waters which was almost exclusively due to the high content of ammonium N (concentration of ammonium N these waters varied between 16.5 and 24.3 mg N/l) (Fig. 7).

The artificial aeration of the lake has contributed to the reduction of nitrogen compounds content, due mainly to reduction of the ammonium N (Fig. 7). In Phase I of the restoration it regarded only the middle section but in

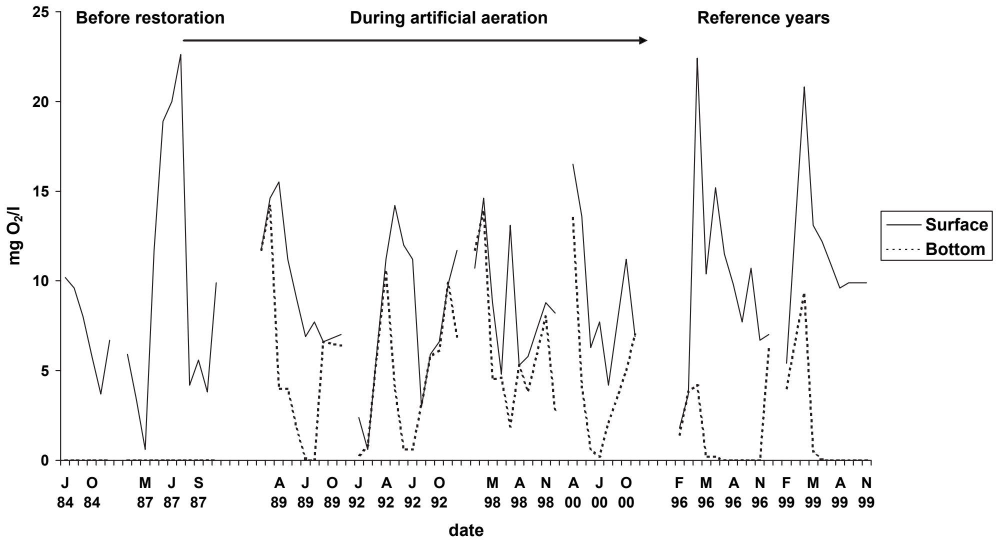

Fig. 3. Oxygen - content changes in the surface and near - bottom waters in Lake Długie in various years (station 2).

Phase II the whole lake. Concentrations of the total N were levelled in the whole water volume and differed in the range of 1.0-3.0 mg N/l (Figs. 6, 7).

Disconnection of the aeration in the reference years, despite an increase of the ammonium N amount, did not cause any major rise of the total N concentration (Figs. 6, 7).

BOD_5

The organic matter content (determined as BOD_5) in Lake Długie waters was variability (Fig. 8). Before restoration, the BOD_5 values were very high and ranged from 1.8-80.0 mg O_2/l while the maximum values were detected in the near-bottom water.

Artificial aeration has caused a very clear decrease of the amount of organic matter. In Phase II of the restoration, the BOD_5 values in the whole water volume oscillated within the range of 2.0-8.0 mg O_2/l (Fig.8).

In the reference years, after disconnection of the artificial aeration, a repeated rise of the content of easily-degradable organic matter was noted (maximum up to 12.0 – 14.0 mg O_2/l near the surface and 12.0 – 20.0 mg O_2/l near the bottom) (Fig. 8).

Transparency

Waters of Lake Długie during the whole analyzed period of the survey were characterized by low transparency, changing in the range of 0.35 to 3.0 m (Fig. 9).

The artificial aeration has stimulated quite radical improvement of water transparency.

Before restoration, the mean value of transparency during the vegetation season equalled only 0.7 m. During the artificial aeration it displayed considerable variations,

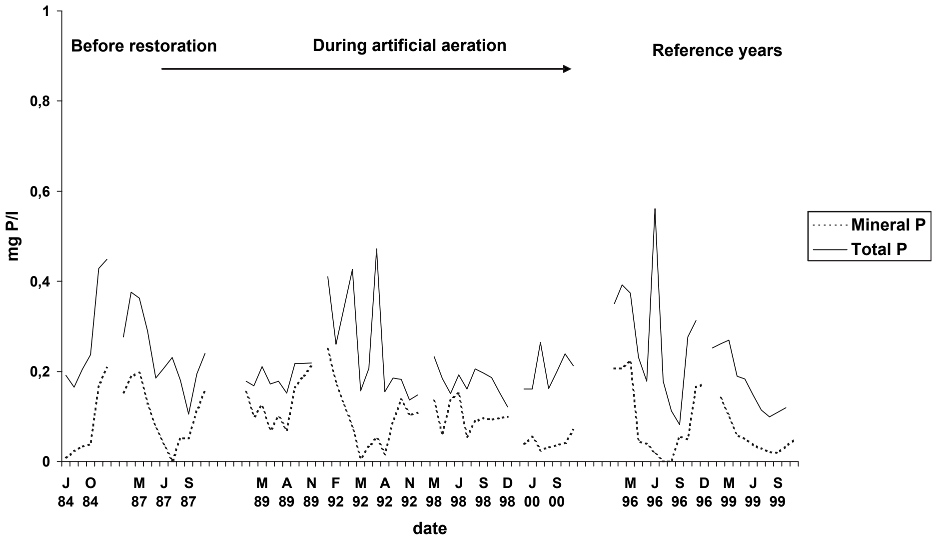

Fig. 4. Changes of mineral - P and total - P concentrations in the surface waters in Lake Długie (station 2) in various years.

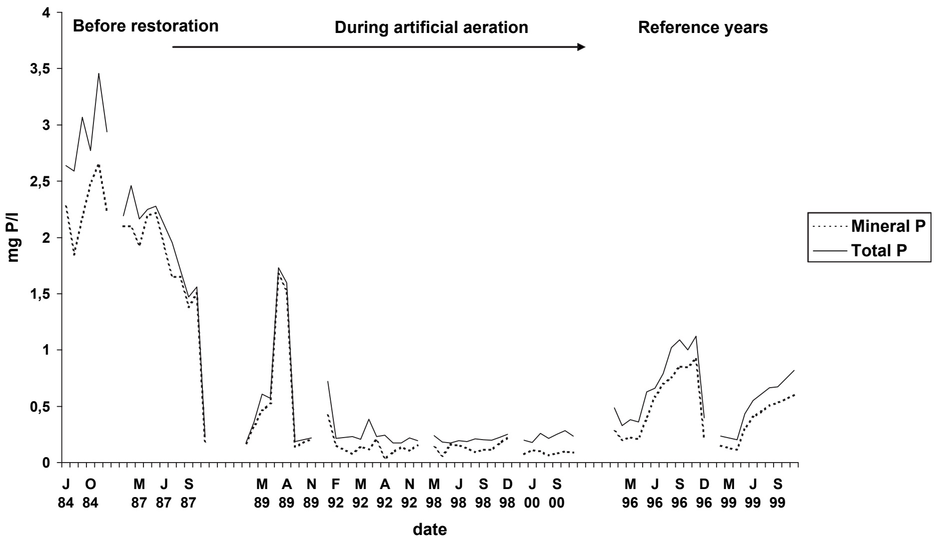

Fig. 5. Changes of mineral - P and total - P concentrations in the near - bottom waters in Lake Długie (station 2) in various years.

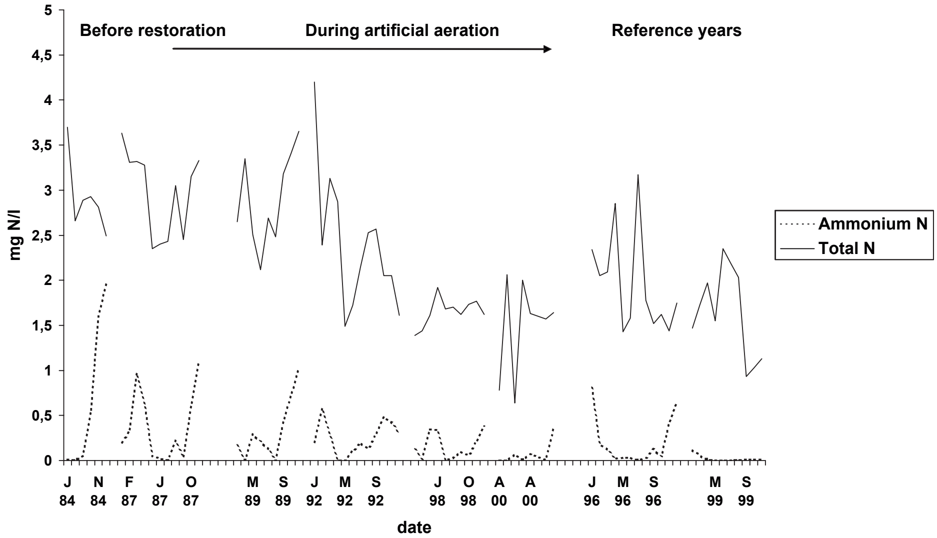

Fig. 6. Changes of ammonium - N and total - N concentrations in the surface waters in Lake Długie (station 2) in various years.

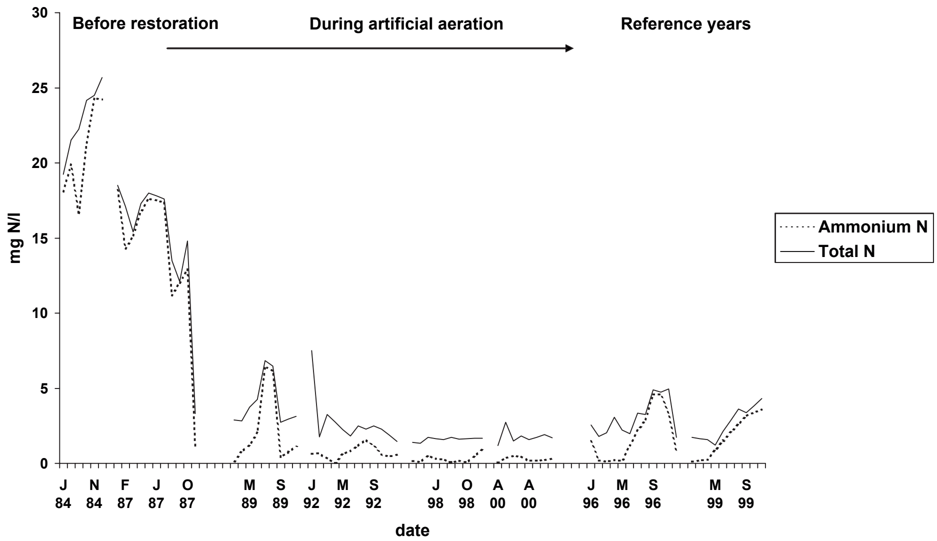

Fig. 7. Changes of ammonium - N and total - N concentrations in the near - bottom waters in Lake Długie (station 2) in various years.

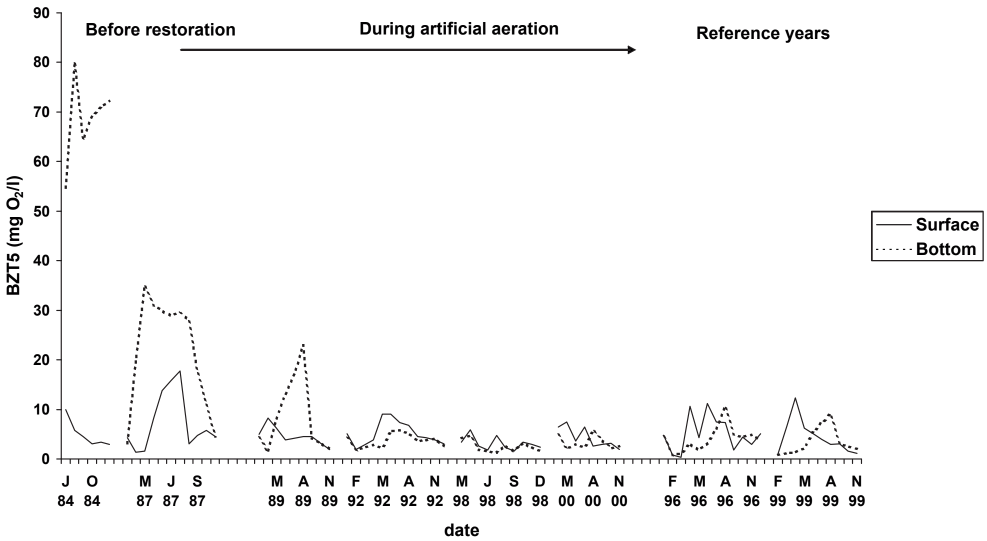

Fig. 8. Changes of organic matter (BZT5) content in the waters of Lake Długie (station 2) in various years.

yet never dropped below 0.5 m, and the mean value was oscillating around 1.0 m. The maximum range of the Secchi disk transparency was noted in the reference years, when the mean value equalled about 1.4 m.

Chlorophyll a

The content of chlorophyll a in Lake Długie during the whole survey was varying in a wide range, i.e. from 0.27 μg/l to 176.4 μg/l (Fig. 10).

The seasonal variability in the chlorophyll a amount consisted of a constant increase of its concentration since spring until the summer peak and then a repeated reduction of its content throughout the autumn turnover. The minimum values were determined in winter (Fig. 10).

Phase I of the artificial aeration had initially caused a small increase of chlorophyll a concentration. A similar phenomenon was also observed in the beginning of Phase II. In the following years a constant decrease of its concentration in the lake waters was noted, with two distinct peaks: in spring and autumn. The mean value of chlorophyll a on all experimental stations in the last year of the artificial aeration (2000) equalled 30 μg/l.

In the reference years, the contents of chlorophyll a were characteristic of high variability. In 1996, a repeated increase of its concentration was determined, whereas in 1999, the concentrations of chlorophyll a detected in the lake waters were the lowest in the whole analyzed period (Fig. 10).

Discussion

The basic principle of the restoration method applied on Lake Długie was mixing of the cold deoxygenated near-bottom waters with the often hyper-oxygenated surface waters. This was achieved through delivery of

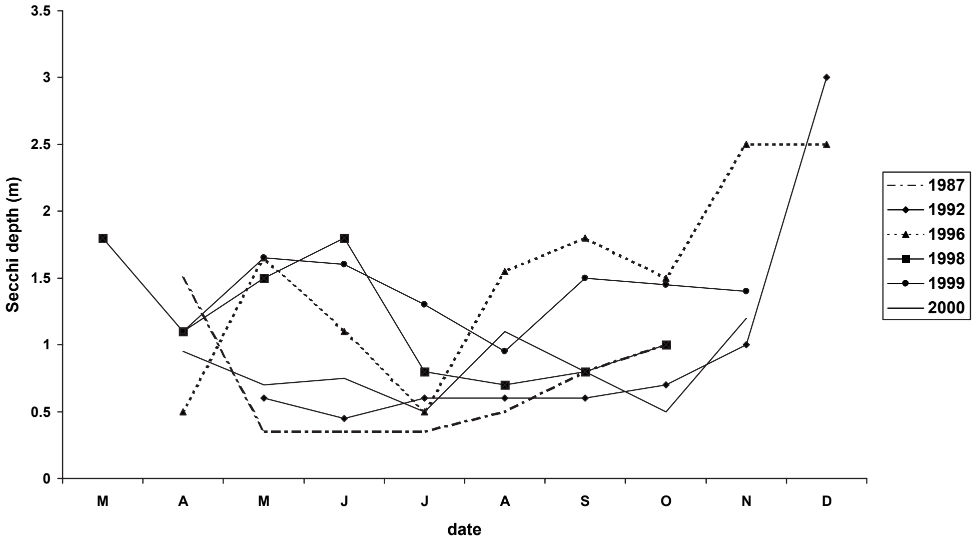

Fig. 9. Changes of water transparency in various years.

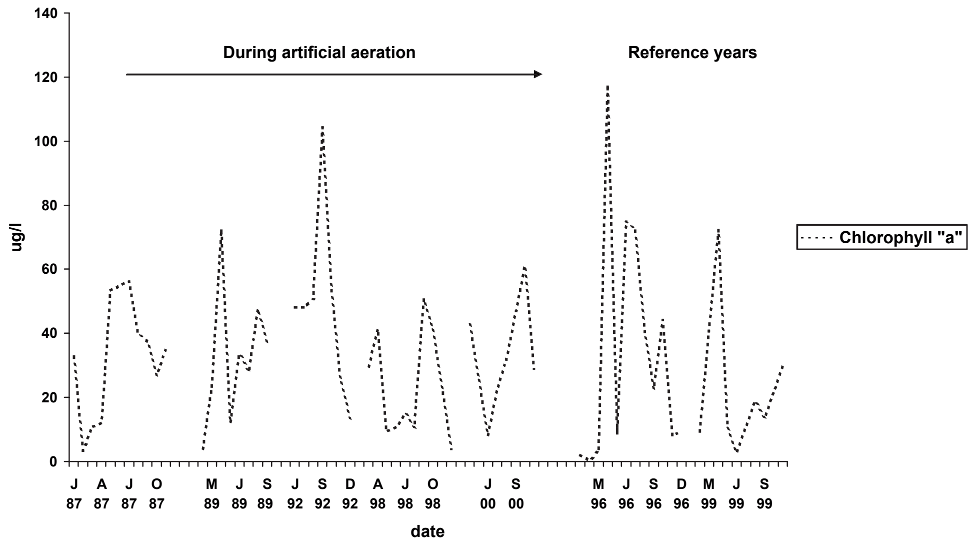

Fig. 10. Changes of chlorophyll a concentration in the waters of Lake Długie (station 2) in various years.

compressed air above the bottom of the deepest spot in the lake. The rising air bubbles were pushing up the near-bottom waters, through the aerator pipe, which resulted in thermal and chemical equalization in the whole water volume.

The air compressor was started up after 3-8 weeks since the ice-cover setting, and then disconnected in the beginning of the autumn turnover. Further water mixing was driven naturally, i.e. caused by circulation and convection movements.

In the examined lake, throughout the whole restoration period difficulties came out in complete destruction of the stable thermal settings. The quantity of delivered air, calculated after [14], in relation to the water volume in Lake Długie should equal 90.5 m^3/h, whereas in relation to the surface area: 96.1 m^3/h. Despite that in Phase I aeration of the lake was accomplished with the use of a compressor with sufficient efficiency (150 m^3/h), the total thermal levelling was observed only in September. It was caused by the use of too-short aerators; thus, the air was delivered 7 m above the bottom.

In Phase II of the restoration much better results were achieved, although the applied compressor with 80 m^3/h delivery rate was of lower efficiency than recommended by [14]. The use of a less efficient compressor was possible due to its preventing stratification set-up instead of its destruction. Nonetheless, in the years 1992 through 2000, in the growing season, small differences in temperature were observed in the water column, caused by a fast warming-up of the surface waters during the rapid increase of the air temperature. Such a situation was pointing out at a too low efficiency of the compressor applied in this phase.

The artificial aeration caused critical modifications to the oxygen settings in the lake. They consisted mainly of a more equal oxygen distribution in the whole water mass and up-keeping of its concentration in the near-bottom waters above 2 mg O_2/l i.e. the concentration regarded as a threshold underneath which the redox potential diminishes [15, 16].

Difficulties constantly arose in sustaining the total levelling in water oxygenation. The most critical period was mid-summer. During all experimental years a fast proceeding deoxygenation was observed of the deepest water. The reason was undoubtedly the acceleration – in the growing temperatures – of organic matter degradation in the deepest water layers and in the bottom sediments.

However, whereas in Phase I of the aeration complete deoxygenation of these waters was not observed, in Phase II the oxygen content practically did not fall below 2 mg O_2/l, and in the shallow northern bay below 5 mg O_2/l. The simultaneously observed decrease of the oxygen content in the surface layers, despite uninterrupted aeration and the still high primary production (high water reaction, low transparency, high chlorophyll a contents), seems to confirm the assumption about the insufficient capacity of the compressor applied in Phase II.

The main issue considered while assessing lake restoration effectiveness is the durability of the achieved improvement of the environmental conditions, especially oxygen conditions.

The results of the reference-years survey have revealed that after more than 10 years of aeration the oxygen conditions in Lake Długie improved considerably. Although in both years the incidents of meta- and hypolimnion waters deoxygenation were noted, the overall period of oxygen-deficits has shortened and the volume of deficient waters was visibly reduced. Before restoration, water in the tropholytic layers was deficient in oxygen practically year-round, whereas in the reference years 1996 and 1999 full deoxygenation was not determined until the start of summer.

A diminished rate of oxygen consumption was observed also during the winter stagnation. At the start of the restoration, the near-bottom layers were oxygen-deficient, yet after about a month since the setting-up of winter stratification, whereas in terminal years that period was extended to about 2 months.

The multi-year utilization of Lake Długie as a receiving water for sanitary wastewater and storm waters from the city of Olsztyn had been displayed by the high concentration of phosphorus compounds in the lake waters and in the bottom sediments [17]. The increased concentrations in lake water, despite the sewage input diversion, was undoubtedly caused by the limited phosphate-removal conditions to the bottom sediments caused by constant deoxygenation of the near-bottom water. In Lake Długie the percentage of phosphorus removed from the water may have been even smaller, due to the low iron content but also due to desorption from the complexes with iron and manganese occurring in the strong-reducing conditions [18, 19].

Phosphates released by both desorption and in the processes of organic matter degradation occurring in the bottom sediments were migrated to the near-bottom water and then, by vertical transport [20] to the trophogenic layer. This process was mostly displayed in spring and autumn. During autumn turnover in lakes reduction of mineral-P concentration in the water can be observed, yet this phenomenon was not observed in Lake Długie. The anoxic conditions in the near-bottom waters and the small amount or even lack of iron in the water disabled its precipitation in the form of iron (III) phosphate.

In Lake Długie 40% of the bottom is situated within the epilimnion range and thus the bottom sediments can play a vital role in nutrient supply. Although the release from bottom sediments in aerobic conditions is lower than in anaerobic [24, 25], nutrients are introduced directly to the trophogenic zone, where they are taken up by phytoplankton [26].

The artificial destratification of waters, like in most of the lakes restored using this method [3, 4, 27], has caused a substantial decrease of total-P in the lake.

In Lake Długie reduction of the total-P quantity was caused mostly by a decrease of the mineral-P concentration, and to a smaller degree of the organic P. As a result of the improved oxygenation of the near-bottom waters, the mineral-P release from the bottom sediments was halted and in consequence its concentration in these waters dropped by nearly 10 times. Limitation of the diffusive release of phosphorus from the bottom sediments (from 1 mg P/m^2·day to 0.3 mg P/m^2·day), resulting from improved oxygen conditions near the bottom of Loosdrecht Lake, was observed also by Keizer and Sinke [28]. However, Gächter and Wehrli [29] do not share that opinion, as based on a 10–year artificial aeration experiment in lakes Baldegg and Sempach they have not determined any decrease of internal loading.

The effect of the reducing conditions on internal water loading with phosphorus was observable in Phase I of the aeration and in the reference years when difficulties occurred to maintain the oxygen conditions. Although many researchers [30, 31] share the opinion that phosphates release from bottom sediments takes place only at oxygen concentrations below 0.1 mg O_2/l. In Lake Długie the maximum release rate was determined at the oxygen content decrease to the value slightly below 2 mg O_2/l.

Nonetheless, attention should be paid to the fact that the quantity of mineral-P was slowly but regularly decreasing in the water of the whole lake and that its quantities were substantially lower than before the restoration and gradually decreasing in the reference years.

The multi-year artificial destratification had much effect on the content of nitrogen compounds. As in the case of phosphorus, the amount was decreased a few times, due mainly to reduction of the ammonium-N content.

Nitrogen content in the water can be reduced through increased sedimentation of organic matter and its deposition in the bottom sediments [22, 32] or by the ammonification of organic compounds and the denitrification to free nitrogen. However, free nitrogen can only be formed after prior nitrification, i.e. oxidation of ammonia to nitrates, occurring in aerobic conditions and in the presence of inorganic carbon [24]. In nitrogen transformations a key role is played by the microorganisms whose activity depends on many environmental conditions.

The first phase of the mineralization of the mineral substance accumulated in the bottom sediments is the ammonification process which leads to release of the ammonium-N to water.

Cerco [19] and Höchener and Gächter [33] report that the release of ammonium-N from bottom sediments to water is promoted by very low oxygen content, or even its total deficit, and by increased temperature. It has been confirmed in Lake Długie in the period before the restoration when the near-bottom waters were oxygen-deficient practically year-round and the ammonium-N was present in large quantities and was in that period nearly the only form of nitrogen compounds.

Improvement of the oxygen conditions in the deeper water layers of the lake caused by the artificial aeration has caused a very fast decrease of the ammonium-N content in the whole lake through oxidation into the nitrate-N. However, it has not been reflected by the nitrate-N content in the lake. The increase of the nitrates content was small due to its uptake by the intensively developing phytoplankton [34], but mainly due to reduction to the gaseous form.

According to Cottingham et al. [35] and Seitzinger [36], denitrification is the major process resulting in nitrogen losses in the aquatic ecosystems. In Lake Długie, during artificial aeration, the denitrification could only take place in the bottom sediments. Nitrates created from ammonia oxidation easily diffuse to the bottom sediments [37], where in the anaerobic conditions subject denitrification into molecular nitrogen.

Disconnection of the aeration and the resultant deterioration of the oxygen conditions had initiated more intense release of ammonium-N from the bottom sediments to the water. The quantities were much lower, though, than before the restoration and were still decreasing in the following years.

In Lake Długie, throughout the whole survey, an intense development of algae was observed which was displayed mostly by the high content of chlorophyll a, low transparency, high reaction and high BOD_5 values. The dominant species in the phytoplankton were blue-green algae, although the increase of transparency and reduction of chlorophyll a concentration in the past years indicates a reduction of the species biomass. Lack of major algae reaction to the diminished concentrations of nitrogen and phosphorus result most possibly from the fact that the concentrations have been still too high to limit the primary production. According to Imboden [30], low fertility of a lake would be guaranteed by spring total-P concentration not exceeding 30 μg/l, whereas in Lake Długie it still exceeds 200 μg/l.

Changes in the content of other chemical indicators were observed only during the aeration and consisted mainly of equalization of the concentrations in the water column. After termination of the aeration, a return to the pre-restoration settings was observed.

Conclusions

1. Multi-year artificial aeration causes gradual but permanent improvement of the environmental conditions in the lake. This has been indicated by: increased oxygen content in the whole lake (at parallel decrease of the hyper-oxygenation in the surface water layers), lowered oxygen-depletion rate during both stagnation periods, and shorter anaerobic conditions in the near-bottom waters.
2. Reduction of the phosphorus compounds quantity in the lake has been caused mainly by the limitation of phosphates release from the bottom sediments.
3. Improvement of the oxygen conditions in the near-bottom waters has had an influence on the content of nitrogen compounds in the lake due to restricted release from the bottom sediments and intensification of the nitrification processes, but mostly due to the denitrifi-

cation process which leads to nitrogen losses through molecular nitrogen release to the atmosphere.

4. The applied 10–year aeration of Lake Długie, despite high reduction of the nutrients amounts, has not resulted in concentrations that would limit the primary production. The lake is still a heavily eutrophic reservoir with intensive primary production.
5. Considerable decrease of the rate of mineral-P concentration diminishment and its still high quantities at the lack of iron and manganese in the water, point out at no conditions for further reduction of the phosphorus compounds in this way in Lake Długie. Further improvement of the trophic conditions in the lake can be obtained only after the application of a supportive method, consisting of phosphorus precipitation and fixing in the bottom sediments.

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