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Attempts to Use Wind Energy for Artificial Destratification of Lake Starodworskie

K. Lossow, H. Gawrońska, R. Jaszczułt

University of Agriculture and Technology,
Department of Water Chemistry and Waste Water Treatment
10-957 Olsztyn-Kortowo, Poland

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Abstract

Attempts at lake restoration by artificial aeration with the use of wind energy were made on the heavily eutrophic Lake Starodworskie. The lake is small (only 7 ha surface area) but 23 m, deep. Artificial aeration was performed using the destratification method. Compressed air produced with the help of a wind turbine was subsequently delivered to the deepest site in the lake. As study results from 1985-87 show, the effects of the applied method were limited. Breaks in aeration caused by lack of winds or too low windpower prevented full destruction of thermal and chemical stratification. However, in the hypolimnion some temperature increase was observed, and oxygenation improvement - minor in summer and considerable in the other seasons. Moreover, the content of organic compounds and nutrients (especially phosphorus) decreased.

Keywords: lakes, restoration, wind energy, artificial aeration, destratification.

Introduction

Artificial aeration is the most frequently applied method of restoration in degraded lakes. It has been practiced world-wide (including Poland) either by complete mixing of waters with thermal destratification or by hypolimnia aeration without destratification. Both ways involve significant energy expenditures in order to produce air in compressors with electrical or, occasionally, combustion drives.

The effectiveness of artificial aeration with destratification has already been tested twice on the experimental Lake Starodworskie in Olsztyn; both times a compressor with electrical drive was applied [1, 2, 3].

The first attempts at hypolimnia aeration were made in 1967-68 [1]. However, the compressor's capacity was too small and the aeration initiated too late (after the onset of thermal stratification), so that no significant improvement in the lake's environmental condition was obtained.

Much better were the results from 1972-73, due to the use of a compressor with doubled capacity and the initiation of aeration before summer stratification. It was observed then that notable improvement of oxygenation in the near-bottom waters occurred, algal blooms during summer stagnation were moderated, and nutrients reduced in the lake waters [2, 3]. However, these favourable changes in environmental conditions in the lake continued for only three years thereafter, and from the mid 70's a gradual deterioration of the lake's trophic condition was observed again [3].

In 1986-89 another restoration attempt was made but this time artificial aeration was augmented by wind energy.

The objective of the experiments carried out on the lake in 1985-87 was to determine the possibilities of employing wind energy for artificial aeration in lakes using the destratification method.

Characteristic of Study Object

The experiments were carried out on Lake Starodworskie in Olsztyn. This lake is a small reservoir (6.99 ha surface area), deep (max. depth 23.3 m; mean depth 7.9 m) and characteristic of the rare (in the conditions of the Mazurian Lake District) relative depth (0.0882) [4, 5]. The basin slopes are leaning sharply towards one well-pronounced hollow in the centre of the reservoir. The lake is situated amid moraine hills of considerable height, overgrown with forest or old trees. On the southwestern, northern and eastern shores are located the buildings and dormitories of the University of Agriculture and Technology in Olsztyn.

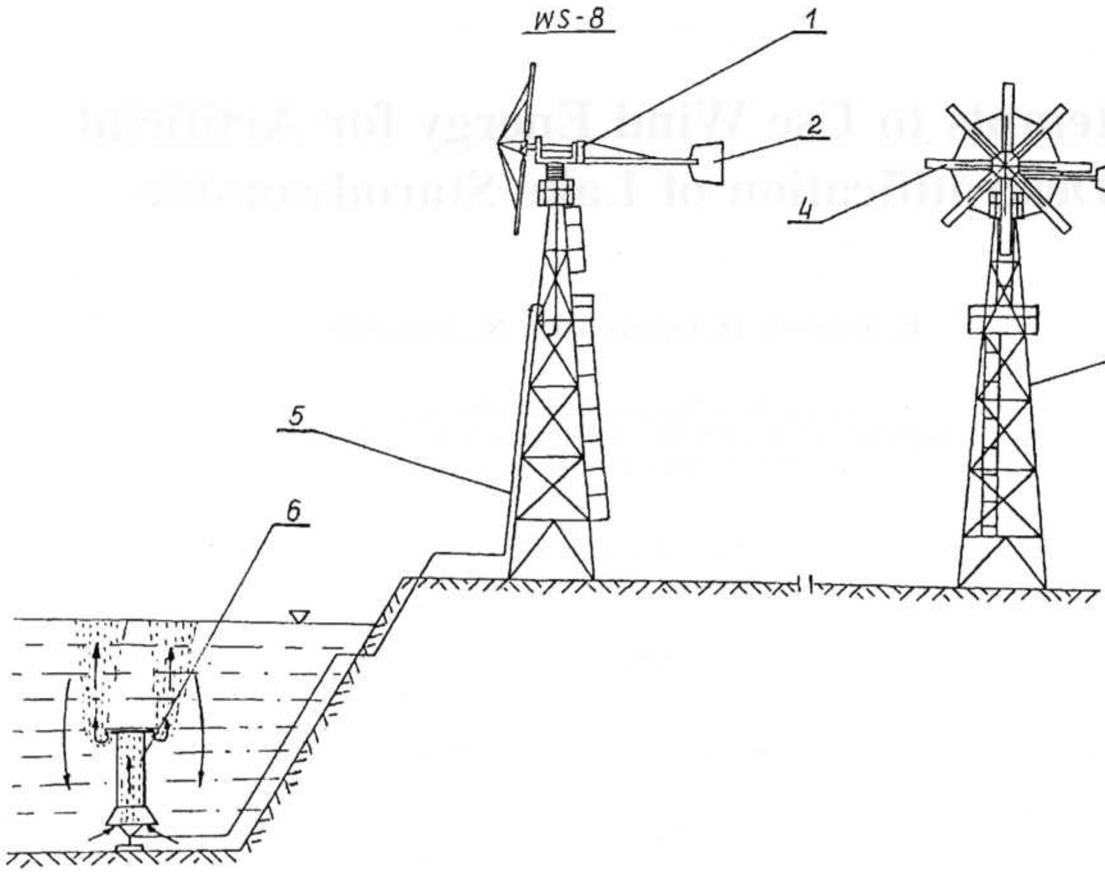

Fig. 1. Schematic view of the destratification system used at Starodworskie Lake: 1 - compressor, 2 and 3 - tail vanes, 4 - wind rotor, 5 - air pipeline, 6 - aerator, 7 - lattice tower.

The catchment area is not large and comes up to 24 ha [6]. The lake has no natural surface inflows. The entire water network comprises the lake basin and an artificial channel, periodically discharging water into nearby Lake Kortowskie.

Methods

In the years 1986-87 artificial aeration of the lake with the use of wind energy was carried out using destratification. In the study a prototype horizontal-axis WS-8 wind turbine was used, with an 8-m diameter rotor. The rotor with 8 blades was founded on a lattice tower and drove 2 air compressors of 40 m^3/h capacity each. Compressed air was then supplied by a 200-m long pipeline to an aerating device drowned in the deepest site of the lake (Fig. 1).

Artificial aeration of the lake was initiated in January 1986 and carried out through the end of 1987 (except for periods with weak winds) and from 28 April till 19 May in 1986 when the devices were turned off after the accident at the Chernobyl nuclear power station. The year 1985 constitutes a reference year in this study.

In order to determine the changes resulting from artificial aeration and to assess the effectiveness of the employed devices, samples were taken from the deepest site in the lake in monthly intervals for physico-chemical analyses throughout the experimental period as well as in the reference year (Fig. 2). Along with sampling, temperature and oxygen profiles were measured at 1-m intervals, and the samples taken at 1, 5, 10, 15, 20 and 22 meters. The analyses were performed in accordance with the "Standard Methods" [7]. Special attention was given to oxygen conditions as well as organic compounds and nutrient concentrations in the lake.

Results

The study on wind turbine effectiveness shows considerable variations in the quantities of air pumped into the lake. The differences were observed from month to month but also between both experimental years. Much more air was supplied to the lake in 1987 (Fig. 3); it was caused by variable wind conditions, complications at the start-up of new devices and failures of the prototype wind turbine.

Lake Starodworskie is representative of exceptionally stable thermal stratification in summer. In 1985 and in the foregoing years [3] promptly after a short and deficient (not deeper than 12 m) spring turnover, summer stratification was set on with an only 2-4 m epilimnion, a thermocline at 8 m and a cold (4-5°C) stable hypolimnion. Autumn turnover was not monitored before the end of November and was either short or just incomplete. In consequence the lake was entering winter stagnation not fully mixed.

The main objective of the artificial aeration was to destroy summer thermal stratification by full mixing in the whole water column.

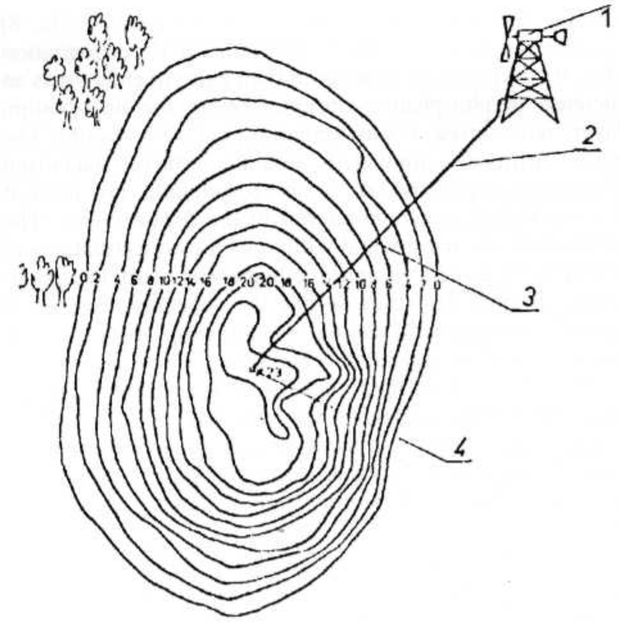

Fig. 2. Starodworskie Lake: 1 - wind turbine, 2 - steel air pipeline, 3 - flexible air pipeline, 4 - aerator.

In summer, despite the prior early initiation of aeration - yet during winter stagnation, the destratification was incomplete (Fig. 4). However, notable changes were observed in the thermal water conditions, especially in the deeper layers: the mean hypolimnion temperature in both vegetative periods increased from 4.2 to 11.8°C in 1986, and from 4.5 to 10°C in 1987, whereas in the reference year it rose by only 0.3°C (from 4.2 to 4.5°C). The maximum temperature increase was monitored in the mid-layers of water. Water temperature at 10 m compared to 1985 was higher by 11°C in 1986 and 6.5°C in 1987. In winter the temperature diminished in the near-bottom water by about 2°C.

The inefficient aeration (long windless periods) and incomplete thermal destratification hindered the preservation of good oxygen conditions in summer; particularly in the deepest water layers (Fig. 5). Although the strong oxygen deficits were shortened by 4 months in the waters deeper than 10 m, in July and especially in August the hypolimnia oxygenation did not exceed 1 mg O_2/dm^3. In the first year of aeration the oxygen conditions were poor, as at the end of summer the dissolved oxygen in the near-bottom waters

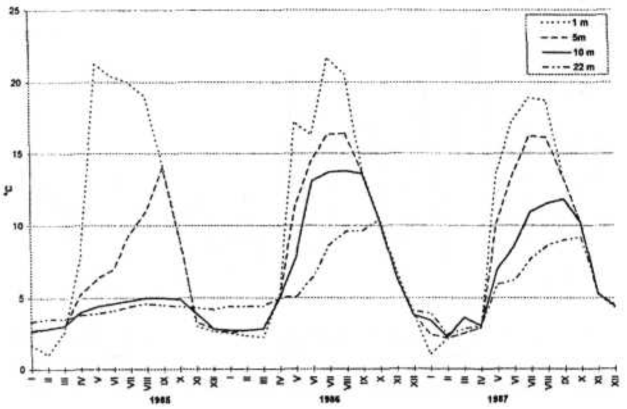

Fig. 4. Seasonal variation of water temperature in 1985-1987.

was fully depleted. Nonetheless, in both experimental years good oxygenation was obtained for all water in spring and autumn, and a considerable improvement of oxygen conditions in winter 1987.

The artificial aeration of the lake influenced the content of organic matter measured as BOD5 (Fig. 6). In 1986 an increase of BOD_5 was evidenced in the whole water column but mainly in the surface layers. In the second experimental year the content of organic matter decreased again, mainly in the deeper layers, where it was 2 times lower than in 1985. This was reflected in the measurements of Secchi disc visibility - a decrease from 2 m (mean value in the vegetative period) in 1985 to 1.6 m in 1986 and a second increase in 1987 to 2.4 m [6].

In 1986-87 spectacular changes in carbon dioxide concentrations in the lake waters were observed. High concentrations in the reference year of up to 75 mg CO_2/dm^3 (51.4 mg mean value) at 22 m decreased during the aeration to max. 60 mg CO_2/dm^3 (35.5 mg mean value) in 1986 and 38.5 mg CO_2/dm^3 (22.5 mg mean value) in 1987 (Fig. 7). In the surface layers likewise in the reference year, CO_2 was present only below the ice cover and during autumn turnover.

Prior to aeration the waters of Lake Starodworskie experienced a high concentration of phosphorus, reaching 0.24 mg P/dm^3 in the surface layers and 1.32 mg P/dm^3 in the near-bottom layers (Fig. 8). Total P content and its seasonal changes were attributed to phosphate concentrations (Fig. 9). Phosphates comprised 62% of the total P on average.

The artificial aeration initiated in winter 1986 brought considerable changes in P concentration in the lake; in both

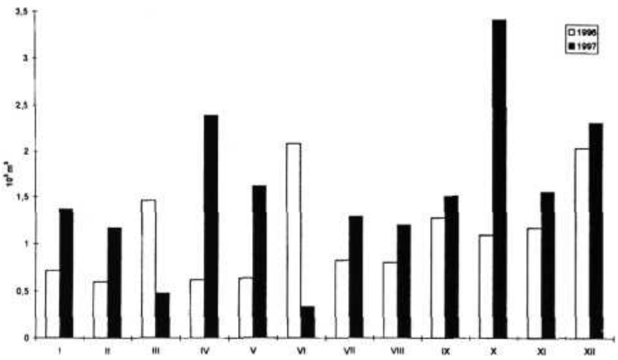

Fig. 3. Monthly air flow rate release at the bottom of Starodworskie Lake.

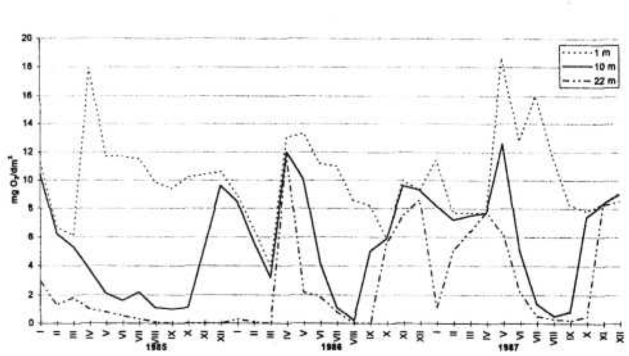

Fig. 5. Seasonal variation of oxygen content in lake water in 1985-1987.

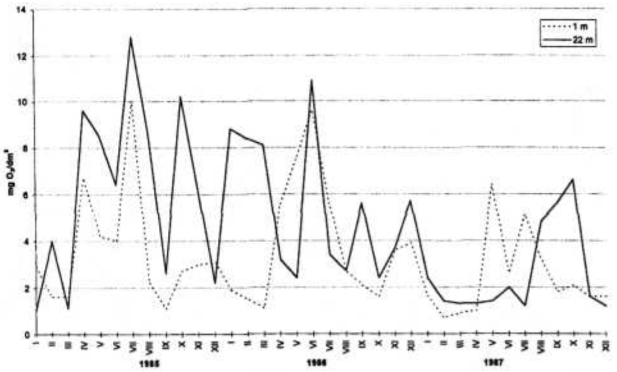

Fig. 6. Seasonal variation of BOD_5 in lake water in 1985-1987.

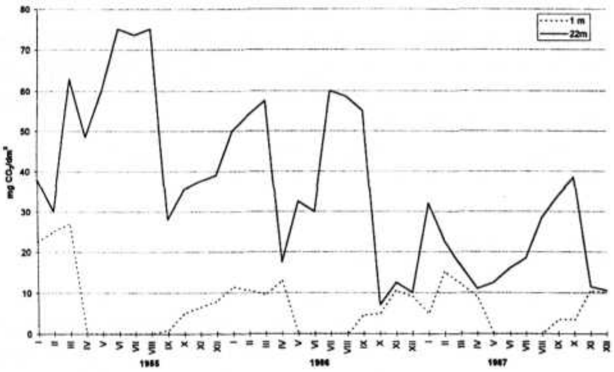

Fig. 7. Seasonal variation of carbon dioxide content in lake water in 1985-1987.

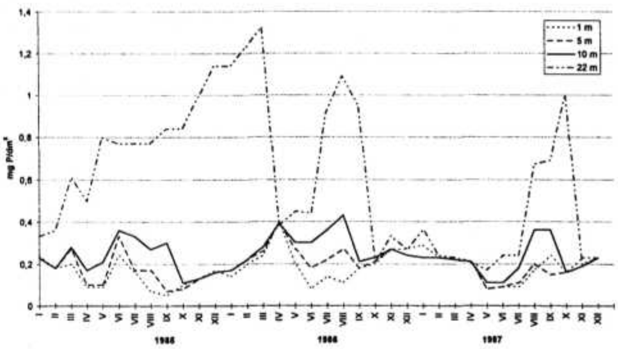

Fig. 8. Seasonal variation of total phosphorus concentration in lake water in 1985-1987.

years it diminished notably in the deepest waters (Fig. 8) mainly due to a decrease in the mineral P concentration (Fig. 9). Although in summer in both experimental years an increase in phosphates concentration in the near-bottom layers re-occurred, it was limited max. to 2-3 months. The early artificially-stimulated autumn turnover equalized P concentration in the lake at an exceptionally low level of 0.2 mg P/dm^3, never monitored in the former years. The relatively even and gradually diminishing concentrations of total P were evidenced until the beginning of summer stagnation in 1987. However, during the vegetative periods in epilimnion the total P content was growing, mostly due to an increase of organic P concentration.

The above-mentioned changes in P concentrations influenced its total content in the lake (Fig. 10). In the first aeration year total P content increased, as compared to 1985, but in the second year decreased greatly; the reason was mainly the diminishing content of mineral and organic P.

The artificial aeration had also an impact on the distribution and content of the nitrogen compounds in the lake.

Before the experiment Lake Starodworskie was recorded for high nitrogen concentrations of up to 4.75 mg N/dm^3 (Fig. 11). Particularly high were the concentrations of N compounds in the deepest water layers. The amount of N was first of all determined by its organic form (70% of the total N on average) although at various water depths its content varied: in the surface layers 87-98%, in the bottom layers only 18-55%, with the prevalence of ammonia N (up to 79% of the total nitrogen) mainly in autumn and winter. Nitrates in larger quantities were present only in winter and at the beginning of the vegetative periods.

The changes stipulated by artificial aeration consisted mainly in considerable uniformity of the total N concentrations in the lake (Fig. 11). Likewise for phosphorus; in the first experimental year total N content increased considerably in correlation with an increase of organic N in the whole lake (Fig. 12), but particularly in the surface waters. In 1987 the average total N content diminished and approached the level recorded in the reference year as a result of the organic and mineral N reduction.

The relatively greatest changes concern ammonia N concentrations (Fig. 13). Its total amount decreased from 125 kg mean value in 1985 to 88.2 kg in 1986 and only 31.5 kg in 1987.

The influence of artificial aeration on nitrate content was less pronounced and noted only in the second year of

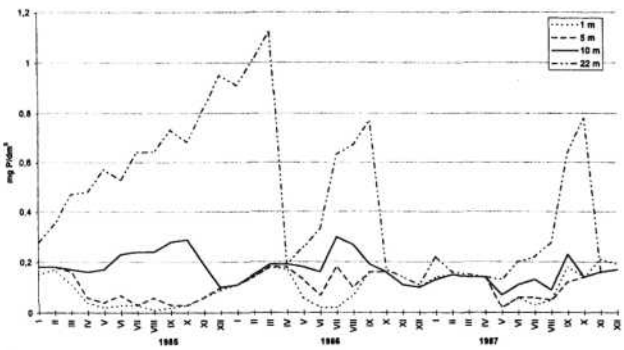

Fig. 9. Seasonal variation of phosphate phosphorus concentration in lake water in 1985-1987.

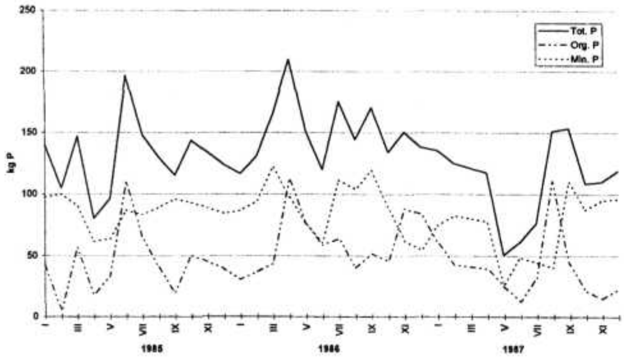

Fig. 10. Changes of total, mineral and organic phosphorus content in water of Starodworskie Lake.

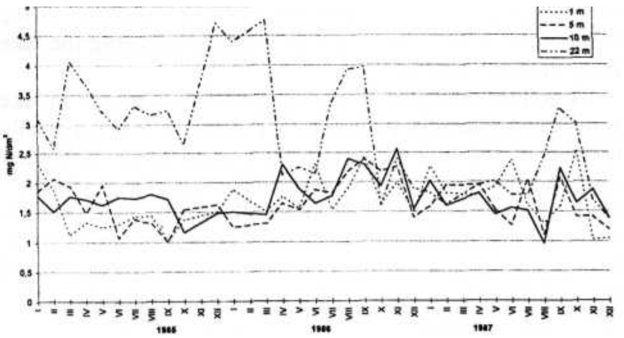

Fig. 11. Seasonal variation of total nitrogen concentration in lake water in 1985-1987.

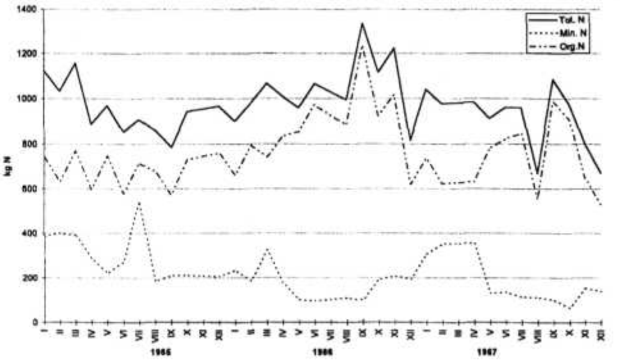

Fig. 12. Changes of total, mineral and organic nitrogen content in water of Starodworskie Lake.

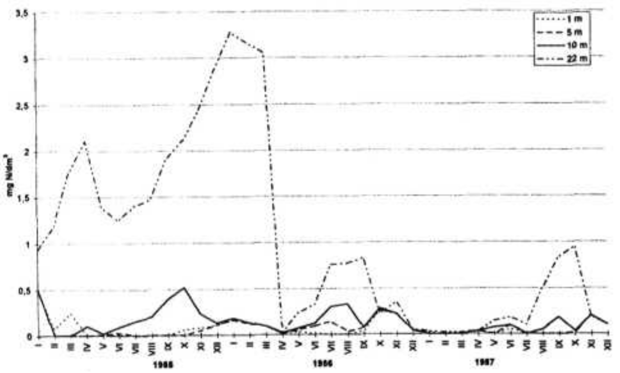

Fig. 13. Seasonal variation of ammonia nitrogen concentration in lake water in 1985-1987.

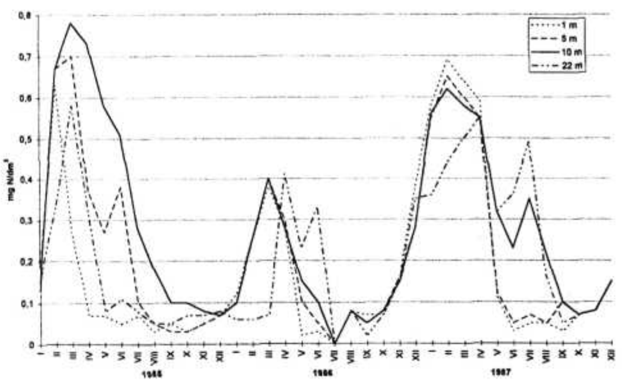

Fig. 14. Seasonal variation of nitrate nitrogen content in lake water in 1985-1987.

the experiment (Fig. 14). The concentration of nitrates in winter 1987 was nearly two times higher than in 1986; the decrease in the vegetative period in the hypolimnion was much slower and the concentration diminished to trace amounts in the whole water at the end of summer stagnation.

Discussion

Lake Starodworskie remains heavily eutrophic despite the two restoration efforts of artificial aeration [1, 2, 3]. As the study by Lossow showed [3], artificial aeration promotes favourable changes in the natural environment of the lake but only for a limited time after its termination. To obtain a stable improvement it might be necessary to carry out aeration for many years [8] and therefore cheaper energy source becomes a precondition. With this in mind, an attempt was made on Lake Starodworskie to replace electric energy with wind energy. The research was meant to select the optimal type of wind turbine and the best method to supply air to the water.

In 1986-87 the lake was aerated with the use of a moderate-speed WS-8 wind turbine with a rotor built according to specifications by the Technological Institute, Eindhoven University [9] (originally used to drive water pumps), and the destratification method.

The major indicator of aeration efficiency in waters is the complete destruction of thermal stratification.

The core of destratification is to actuate the water mass dynamism. Compressed air bubbles coming out near the lake's bottom comprise transport medium, whose role is to bring the cooler near-bottom waters up to the surface in summer and the warmer waters in winter, at the same time mixing the whole water column. This requires efficient aeration that destroyes the thermocline and subsequently equalizes the temperature or otherwise - if aeration is started early enough - prevents the onset of thermal stratification.

This method of aeration was employed in the first phase of aeration. In both years prevention of the thermocline onset was unsuccessful although significant temperature increase in meta- and hypolimnion was observed (Fig. 4).

The waters in Lake Starodworskie are exceptionally stable [3], [10]. Based on the work of Lorenzen & Fast [11] we can calculate that in order to destroy the thermal stratification in this lake and sustain homothermy, the capacity of a compressor should be at least 0.5 m^3/min. The study has shown that the daily delivery of air from the WS-8 turbine covered merely 55% of the theoretical demand. The reason was mainly the high start-up speed of the engine - 3.6 m/s with one compressor and even higher - 4.9 m/s with two compressors. Consequent breaks in the wind turbine work occurring not only on windless days but also at weak winds, forced to turn off one compressor, limiting the efficiency of air supply. Additionally unfavourable is the fact that in the Mazurian Lakes District weak winds prevail in summer [12], which considerably restrains the applicability of the discussed aeration system.

The main objective of artificial aeration in deep stratified lakes is to improve oxygen conditions in the deepest water layers. Oxygen stratification in Lake Starodworskie is exceptionally unfavourable [2, 3, 10]: the epilimnion is oversaturated and the hypolimnion and metalimnion become anoxic, even in May. A similar pattern was observed in 1985 before the experiment (Fig. 5).

Attempts to destroy the exceptionally stable thermal system and the subsequent oxygen stratification by means of wind power were unsuccessful. Although the water in winter, spring and autumn was better oxygenated, in summer the improvement in oxygen conditions near the bottom was insignificant. As later revealed, the efficiency of the devices was too small to fully destroy the stratified system. But it was sufficient to rise the hypolimnion temperature and consequently to accelerate the decomposition of organic matter in the water and in the bottom sediments (eventually increasing the dissolved oxygen demand and causing oxygen deficits at the end of summer). Difficulties in preserving good oxygen conditions have yet been reported for other artificially aerated lakes [13, 14, 15, 16, 17]. In the case of wind turbine application with destratification method the major danger is device shut-down due to weak winds or windless periods which occurr often in the Mazurian Lake District in summer. Similar phenomenon of a sudden deterioration of oxygen conditions in the near-bottom waters was observed by Lossow [3] at the failure of the electrical compressor. The danger of breaks in air delivery coming from insufficient wind conditions seems to be the major obstacle in destratification supported by wind power.

Despite the above, artificial aeration has caused considerable change in environmental conditions in the lake. The amount of easily degradable organic matter in the deeper layers decreased, as well as the amount of CO_2 migrating to the atmosphere. Other authors have revealed similar findings in studies on lake aeration [8, 16, 18, 19]; the decrease in total P content in water was monitored in Lake Starodworskie, although during the less intensive turnover in 1986 it increased. The experiments confirm the thesis by Lossow [3] that too extensive mixing of waters can result in the acceleration of primary production in the lake. Such mixing does not prevent the internal nutrient supply; instead, the nutrients are transported to the euphotic layer. Nevertheless, a decrease in mineral P in the near-bottom waters, as compared to 1985, might indicate that the release of phosphates from the bottom sediments is limited even if circulation is not so intensive. An increase of P content in bottom sediments evidenced by Gawronska [6] seems to prove that.

An increase in P content in the lake was observed only after prolonged oxygen deficits in the hypolimnion, accompanied by mixing of the near-bottom waters with the less rich surface waters. We can therefore conclude that significant P release during aeration was taking place mostly from the hypolimnetic sediments. Maximal release velocity was always recorded when the conditions altered from aerobic into anoxic; the notably higher maximal values [6], as compared to 1985, confirm the thesis of many researchers [20, 21, 22, 23, 24, 25, 26] that temperature increase and enhancement of water mass dynamics intensify the process.

Changes in total N content were not as spectacular as in the case of P. The changes consisted mainly in equalization of its concentration in the whole water column as a result of a decrease in the hypolimnion with a parallel increase in surface waters, and considerable reduction of ammonia N in the deeper layers. The effectiveness of artificial aeration in N reduction was not fully confirmed in the study. Measurements have shown that the N compounds were subject to reduction [3, 8, 16], and increase, but this also varied in the individual years [28]. Garrell *et al.* [29] and Lossow [16] explain sudden changes in N content in the individual aeration years with N loadings entering the lake from external sources.

A greater reduction of phosphorus than nitrogen in lake waters consequently increases N:P ratio. It was especially notable in the second year of the experiment. Schindler [30] and Schindler & Fee [31] emphasize the positive effects of such increases in lakes. Based on this, we can conclude that in all methods of lake protection and restoration special attention should be paid to reduction of internal and external phosphorus loadings and that attempts to reduce nitrogen loadings can have a reversed effect.

The results of the study have shown that, at least in the conditions of the Mazurian Lake District (with low wind-power or frequent windless periods in summer), the application of wind turbines in lake restoration by destratification method should not be recommended. Presumably a much better solution is hypolimnion aeration without thermal destratification.

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