Original Research

Assessment of the Multi-Directional Experiment to Restore Lake Góreckie (Western Poland) with Particular Focus on Oxygen and Light Conditions: First Results

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Abstract

Our paper presents the study results of the first year of restoration of Lake Góreckie in Wielkopolska National Park. The restoration was carried out on several levels which involved: aeration of the hypolimnion using the pulverizing aerator with wind drive, phosphorus inactivation by iron coagulant, and reduction of plankton-eating fish. The comparison of the results obtained in the year 2010, that is in the time of the implementation of restoration procedures, with the results of similar studies conducted before the restoration, in 2008 revealed an increase in water transparency that resulted in the greater range of visible radiation from the photosynthetically active scope, which unfortunately did not improve the oxygen condition in the water depth. The effects of the hypolimnion aeration were not observed, even at the sampling station situated 20 m from the aerator. In the sub-bottom zone, the decrease in phosphate concentration was observed, with the concentration of ammonium nitrogen staying at the same level, which indicates the effectiveness of phosphate precipitation.

Keywords: lake restoration, pulverizing aerator with wind drive, iron coagulant, dissolved oxygen, light conditions, *Cyanophyceae* blooms

Introduction

The eutrophication of surface water is one of the main negative effects of human pressure on the environment [1, 2]. This process refers to the majority of Polish lakes, in which a rapid growth of phytoplankton, defined as bloom, occurs in the vegetation season. The bloom results not only in the worsening of the organoleptic and hygienic properties of water, but also in far-reaching changes in the functioning of the whole water ecosystem [3]. The abundant bloom of phytoplankton causes strong absorption of sun radiation and the euphotic zone becomes significantly shallower [4]. Dramatic worsening of light conditions in deeper water zones results in the destructive processes prevailing over the productive ones in the dysphotic zone. In the deep lakes, however, the largest surface is occupied by the aphotic zone, where photosynthesis does not occur. The abundant growth of *Cyanophyceae* and algae causes quick depletion of available nutrients from water. The consequence is their slow decay and sedimentation from the productive euphotic zone

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to the sub-bottom layer, where their decomposition takes place, first aerobic and, after the exhaustion of oxygen, anaerobic [5, 6]. The above process expands the zone of totally oxygen-free water, inaccessible to most breathing organisms. Not only is the biological balance of ecosystems disturbed, but also the direction of abiotic changes.

The European Water Framework Directive [7] that imposes upon member EU countries the obligation to improve the ecological condition of the lakes by the year 2015, initiates the activities aimed at restoring the original, good state of water. The first and most important step aimed at renovating a lake ecosystem is cutting off all the external biogene sources, both the ones referring to particular points and those regarding particular areas. Most often, however, such activities are insufficient. This is caused by nutrient-rich sediments (mostly compounds of phosphorus and nitrogen) deposited at the bottom of a lake, which, in favourable conditions, are released again and become the internal source of biogenic compounds [8, 9]. The mobility of phosphorus compounds is supported by the deoxygenation (reductive conditions) of water, which usually occurs at the bottom zone. The nitrification of the ammonium nitrogen, released as a result of mineralization of organic matter and toxic for the hydrobionts, becomes impossible. Toxic hydrogen sulphide appears in water. In stratified lakes, during the stagnation period, in the bottom zone, a significant increase in biogenic substances concentration is observed [10-12].

Artificial aeration is the most frequently applied method of restoration in degraded lakes [13]. The great majority of lake recultivation techniques applied worldwide are based on artificial aeration with simultaneous thermal destratification or with no destruction of stratification [14, 15]. The above methods are marked by various levels of interference with the lake ecosystem. In the case of Lake Góreckie, a complex restoration using chemical methods: 1. oxidation of bottom water and 2. iron addition to the water/sediment to improve the phosphorus-binding potential (with relatively little interference with the ecosystem) and biological methods with removal of non-predatory fish were selected. The aim of our study was to establish the effects of these activities in the first year of restoration. A subject of particular focus was the assessment of effectiveness of oxygenation of the lake with the application of a wind-powered aerator.

Study Area

Lake Góreckie in Wielkopolska National Park is a post-glacial, ribbon lake. The weakly developed shoreline borders on the forest, which covers 59% of the catchment area. During the last 10 years, this contribution has increased by 10% [16]. The large supply of the catchment minimizes the influence of agriculture on the lake, and especially of fertilization and other agricultural procedures. The lake basin is naturally divided into two sub-basins (Fig. 1): a deep southern one, with steep slopes and depth of 10-15 m on almost 1/3 of its area (max. depth 16.5 m), and a shallower north-western one with a depth of 5-10 m. On the lake are two forest islands. At the beginning of the 20th century, the lake area was 105 ha, total length 3,025 m, average width 347 m, maximum depth 17 m, and average depth 9.5 m [17]. Since that time, a constant lowering of the water table has been observed. In 2002, the lake had an area of 101.6 ha, a maximum depth of 16.6 m, and average depth 8.5 m [16].

Lake Góreckie is mainly supplied by groundwater from the upper interloam water-bearing level and from the Wielkopolska buried valley aquifer, as well as to a lesser extent by atmospheric precipitation. This is shown in the linear dependence of the lake water level on the level of groundwater in the Wielkopolska buried valley and the lack of direct correlation between atmospheric precipitations [16]. The shallowing of the lake may be caused by the influence of a depression crater formed as a result of pumping out water for the Poznań agglomeration at the Krajkowo well-field. As a result of the water level decline, the lake has had no outlet for many years. For over forty years, the lake has served as a tank for treated sewage from the palace buildings in Jeziory, which held a sanatorium [18]. This source of pollution was eliminated in the late 1980s. Despite the implementation of the complex sewage management system (pumping sewage outside the lake catchment) and the favourable catchment structure, the condition of lake water continuously deteriorated. This was directly reflected by the extensive phytoplankton bloom every year and the deoxygenation of metalimnion and hypolimnion in the vegetation season [19]. As a result, a discussion on the lake restoration was initiated. Due to the fact that the lake is located in a national park, the choice of a method with relatively little interference with the ecosystem was justified. Following consultations with academics, a wind-driven pulverizing aerator was installed, which aerates the hypolimnion without disturbing the thermal stratification of the lake. The method of hypolimnion aeration is based on mechanical removal of hypolimnetic water, oxygenation in the air, and return back to the same depth without changing temperature. The disadvantage of this method is poor gas exchange efficiency. Hypolimnetic aeration is not recommended if maximum depth is less than 12 to 15 m [20].

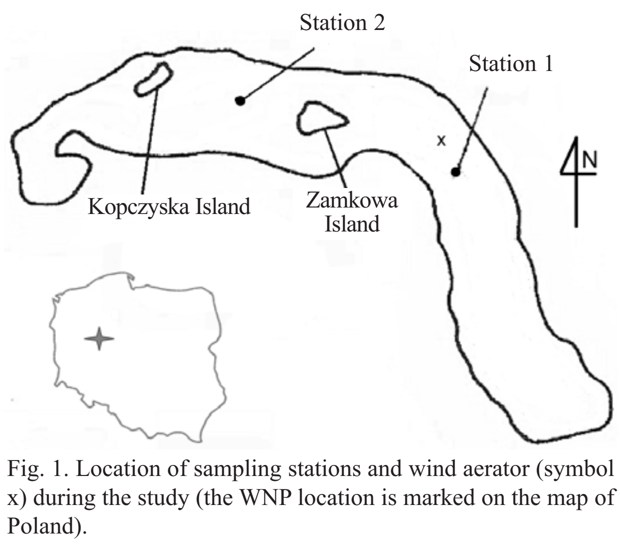

Fig. 1. Location of sampling stations and wind aerator (symbol x) during the study (the WNP location is marked on the map of Poland).

The principle of operation of pulverizing section of wind-powered aerator consists of working a paddle wheel (1), and transferring water from the suction chamber (2) to the pumping chamber (3), during which pulverization of water occurs, allowing for gas diffusion [21] (Fig. 2).

The aerator was launched in December 2009. Due to the prolonged lake icing, the aeration of the hypolimnion started at the end of April 2010. In the spring period (April, May) the procedure of phosphorus inactivation using iron(III) sulphate(VI) and coagulant (chemical formula: $Fe_2(SO_4)_3$) was performed several times (coagulant was applied from the application boat to the whole lake). Sampling and selective collection of ichthyofauna was also performed in the summer. In total, about 3 tons of fish, mainly small roach and perch, were caught.

Methods

The study was conducted in the year 2010, the first year of the lake restoration. Every month, at sampling stations 1 and 2 located in the deepest point of the southern basin and in the deepest point of the northwestern basin respectively (Fig. 1), *in situ* in the vertical profile of the lake, every one meter, the following indicators were measured: temperature, dissolved oxygen and oxygen saturation, pH and conductivity, using a multiparameter sonde (Multi 350i, WTW) with a probe with a rotor inducing water movement in the sampling area. Additionally, the measurements were performed at the sampling station at a distance of about 20 m from the aerator (leewards) in order to evaluate its influence on water aeration. During the whole study period, the device was anchored about 80 m north from station 1, at a depth of 16.5 m. Due to the diurnal dynamics of oxygen, temperature, and height of the sun above horizon, the research was undertaken between 11 a.m. and 2 p.m. Measurements were carried out in all weather conditions.

Water transparency was measured using a Secchi disc (white, diameter 30 cm). In order to establish the actual range of light in water and the euphotic zone thickness, the rate of photosynthetically active quantum radiation (PAR) was measured using the spherical quantum sensor (LI-COR 193SA with the LI-1400 datalogger). The spherical sensor expands the range of underwater study of light as it enables the measurement of total radiation. The bottom limit of the euphotic zone is the depth reached by 1% of light penetrating the water surface. In the paper, two ranges of the euphotic zone have been presented: $Z_{1\%}$ and Z_4 (as 4 $\mu mol \cdot s^{-1} \cdot m^{-2}$), being the variants of the minimum amount of photosynthetically active radiation sufficient to initiate the process of photosynthesis [22]. In both variants, the depths of radiation penetration were investigated using *in situ* method.

Water samples for laboratory study were collected from depths of 0.5 m and 14 m at sampling station 1 and from depths of 1 m, 0.5 m, and 10 m at sampling station 2. The determinations of ammonium nitrogen, nitrate, nitrite, organic nitrogen, total phosphorus, and dissolved phosphates [23] were performed. Similarly, monthly investigations at stations 1 and 2 were conducted in 2008 [6].

Results and Discussion

Summer 2010 was exceptionally hot, which was reflected by very high water temperatures. Thermal stratification of water stabilized as soon as April and stayed at the same level until the end of September (Fig. 3). At the peak of summer, as a result of intensive insolation, a shallow mixed layer was formed – in June and July it was only 2 m deep (maximum temperature 27.2ºC). The thermocline was

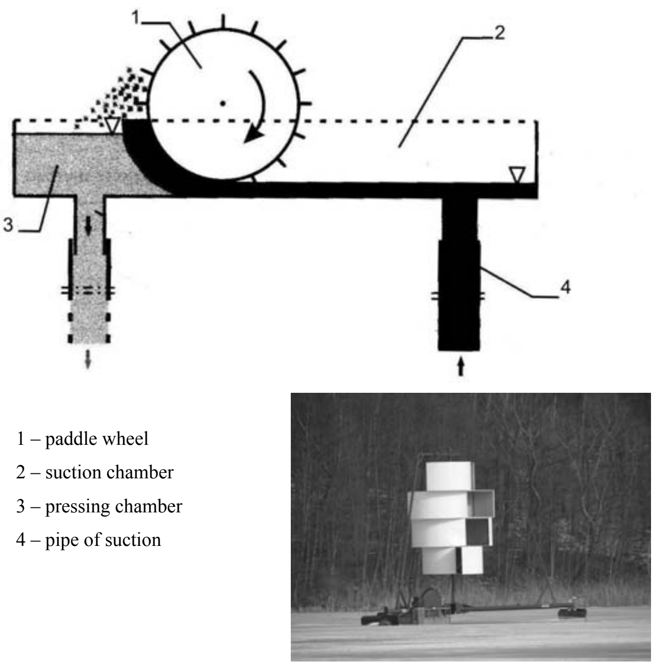

Fig. 2. The scheme of the pulverizer operation [after 21, changed] and photography of the pulverising aerator with vertical Savonius turbine on Lake Góreckie.

very sharply marked, and the temperature gradient was high (maximum 14.1ºC). The year 2008 was significantly colder – the thermal condition of water characteristic for the summer stagnation period was observed in the period from May to September. The thickness of the epilimnion zone ranged from 2 m in June to 5 m in August. The thermocline was usually 3 m thick, and the temperature decreased to a maximum 8.2ºC (June-July).

The epilimnion was highly over aerated while in the upper layer of metalimnion (below the depth of 3 m) the water was completely deoxygenated (anoxia). An extreme range of anaerobic zone was observed in the lake (Fig. 3). Very similar oxygen conditions of water were found in 2008, the only difference being that the whole depth of water was well aerated as late as April. This was the consequence of the rapid worsening of weather conditions at the end of March (low temperatures and strong winds), which stirred the lake down to the bottom. As a result, the homooxygenic conditions and 100% oxygen saturation from the surface to the bottom was observed in the whole lake basin [6]. The study of oxygen concentration in water at the sampling station at the aerator showed that during the whole study period, the vertical distribution of dissolved oxygen did not differ from the distribution observed at station 1. The thickness of thermal zones and water transparency were also found to be the same.

The average value of water transparency found during the study period amounted to 2.5 m, that is 0.5 m more than in the similar period in the year 2008 (Fig. 4). The value ranged from 1.1 m in June to 5.05 m in September. It should be mentioned that the value found in September was the highest of all recorded for many years and it was comparable to the one observed in the 1930s [17]. Unfortunately, the change was short-lasting (decrease to 3.7 m in October) and it did not result in any significant improvement of oxygen conditions. At that time, the anaerobic zone comprised a part of the metalimnion and hypolimnion (Fig. 3). During the whole study period, from a depth of about 10 m, hydrogen sulphide occurred in water, indicating the intensive, anaerobic decomposition of organic matter.

In 2008, the worst light conditions in the lake were observed in May with the rapid growth of phytoplankton

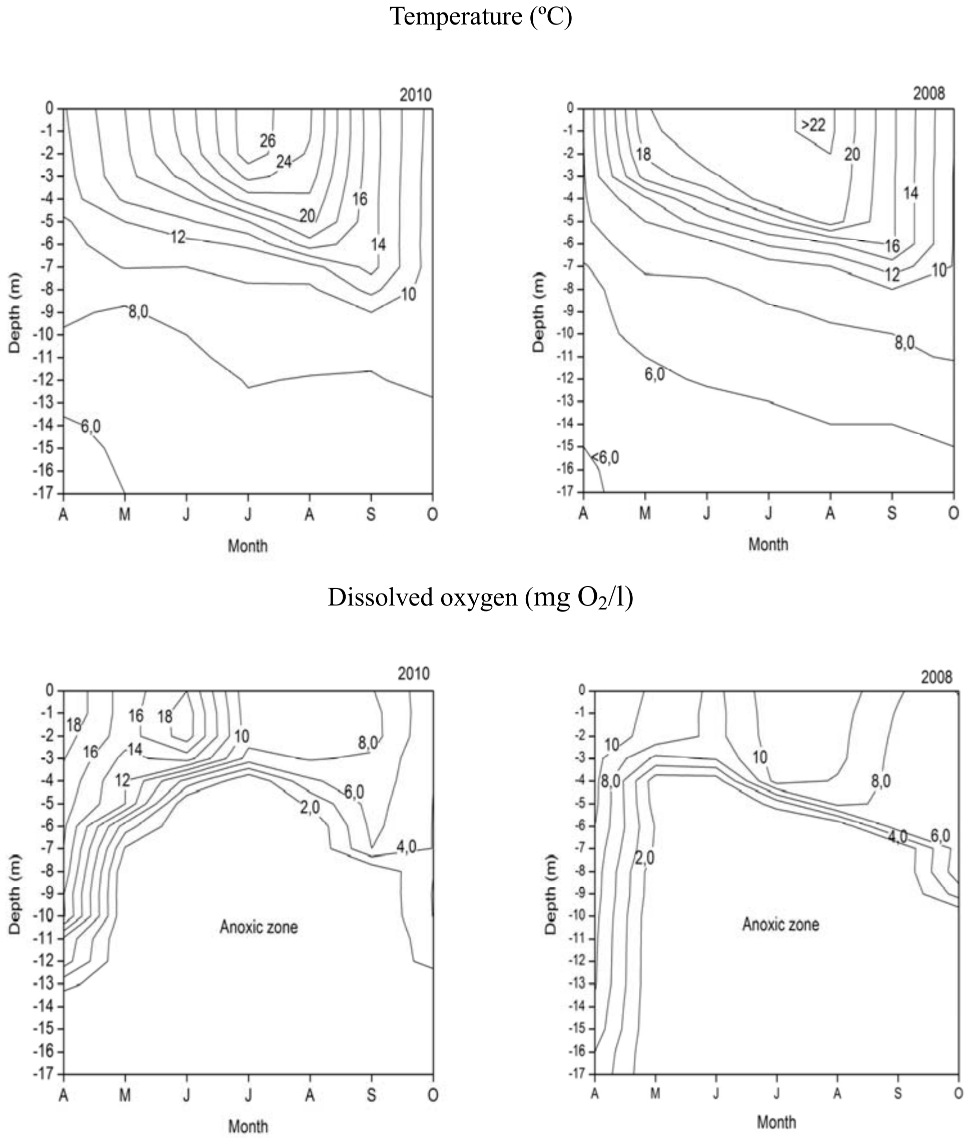

Fig. 3. Comparison of vertical changeability of water temperature and dissolved oxygen concentration at station 1 in 2010 and 2008.

and the bloom of *Cyanophyceae*. This resulted in a high increase in water turbidity and the limitation of light range as a result of dispersion and absorption. In the Secchi disc visibility range, strong dispersion of light and the illumination of water depth were observed [4]. The characteristic feature of light conditions in the lake is their continuous (every year) improvement at the peak of summer, usually in July or August.

The analysis of the penetration of photosynthetically active scalar radiation revealed a large dispersion of the euphotic zone depths. The range of zone $Z_{1\%}$ was from 2.8 to 6.0, and Z_4 from 3.2 to 7.7 (Fig. 4). The values of scalar PAR intensity at $Z_{1\%}$ depth ranged between 5.7 and 22.5 μmol·s^{-1}·m^{-2}, with an average 5.5 μmol·s^{-1}·m^{-2}. This indicated the accessibility of light with enough energy to initiate photosynthesis and release oxygen. In the months starting and finishing the vegetation period (April and October), no close relationship between the light range and the zone of photosynthesis and oxygen concentration in water depth was observed. In the remaining period, oxygen did not occur below the borderline of the over-illuminated zone, which strictly referred to the range of photosynthesis. This tendency, however, was not constant. At the peak of summer (July-August), the PAR penetrated to over 2 m into the anaerobic zone, which indicated an exceptionally high demand for oxygen in the processes of organic matter decomposition. Also in the euphotic zone, the processes of oxygen release may not compensate for its decline.

The chemistry of lake water in 2010 was similar to the year 2008. In the vegetation period, in the epilimnion, mineral forms of nitrogen and phosphates were unavailable due to their total exhaustion in the primary production process. High concentrations of nitrogen and phosphorus compounds were observed in the sub-bottom zone. In 2008, the concentration of ammonium nitrogen ranged from 0.4 mgN·L^{-1} in the period of spring mixing to 9.6 mgN·L^{-1} in November, when the sub-bottom layer was not yet mixed. Similarly, in 2010 during the spring mixing, the concentration of ammonium nitrogen amounted to 1.4 mgN·L^{-1}, while in November, shortly before the autumn mixing, it also amounted to 9.6 mgN·L^{-1}. In both years, the average annual concentrations of ammonium nitrogen in the sub-bottom layer were almost equal, and they amounted to

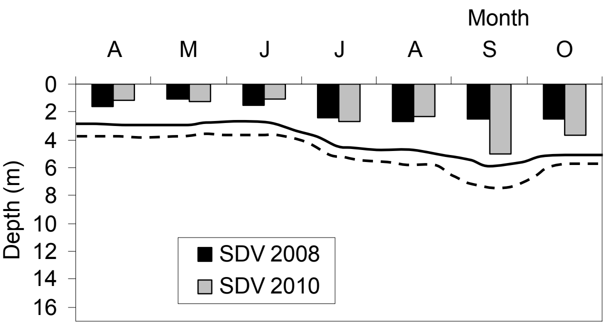

Fig. 4. A comparison of Secchi disk visibility (SDV) from April to October in 2008 and 2010, and depth of the euphotic zone in variant $Z_{1\%}$ (solid line) and Z_4 (broken line) in 2010.

about 3.9 mgN·L^{-1}. Similarly in the case of phosphates, in 2008 the lowest concentration in the sub-bottom zone (to 0.64 mgPO$_4$·L^{-1}) was determined during the spring mixing, while the highest concentration (2.60 mgPO$_4$·L^{-1}) was determined in November, before the autumn mixing. In the year 2010, the concentration of phosphates was lower and it amounted to 0.30 mgPO$_4$·L^{-1} and 1.00 mgPO$_4$·L^{-1}, respectively. Only in February, before the inactivation of phosphorus began, were phosphate concentrations higher (max 1.50 mgPO$_4$·L^{-1}) while in the year 2010, in the restoration period, they were much lower (max 0.62 mgPO$_4$·L^{-1}), which was undoubtedly the result of phosphate precipitation using iron coagulant. However, because the bottom waters were permanently deoxidized, this state could be only temporary. Generally, anaerobic conditions promote mobilization of phosphorus, especially from binding with iron [24]. Consequently, bottom sediments may provide an important source of phosphates transferred to the water column [8, 9, 25].

The year 2010 brought slight improvement of light conditions, caused by the less intensified growth of phytoplankton. This phenomenon might have been caused by a lower biological concentration of assimilable phosphates, following the procedure of dosing iron coagulant in spring, and the fact that repeating the procedures of dosing the coagulant might have disturbed the ecosystem mechanically and chemically, resulting in the partial decay of phytoplankton or its coagulation. This concerns especially the *Cyanophyceae*, which are not resistant to the turbulent water movements [26] generated by boats used to apply the coagulant. Unfortunately, already in June due to stabilization of the lake water environment cyanobacteria bloom appeared again (mainly *Limnothrix redekei*). The late summer increase in water transparency may be a consequence of reduction of the population of plankton-eating fish and greater pressure of zooplankton on phytoplankton.

In Summary, the improvement of light conditions observed in 2010 did not bring the expected improvement of oxygen conditions for the lake. In summer, despite the relatively good water transparency, the zone of well aerated water comprised the shallow epilimnion and barely reached the upper part of metalimnion. Similarly bad oxygen conditions were found directly at the aerator, which would explain no visible effects of its operation. The causes for such a state of things should be seen in insufficient efficiency of the device, definitely not adjusted to the scale of oxygen demand in the lake. In order to reach the level of oxygen concentration in the sub-bottom layer (1 m thickness) at the level of 1 mgO$_2$·L^{-1}, the total amount of 1000 kg O_2 would have to be introduced. At the same time, one should remember that vast amounts of oxygen are constantly used in the mineralization processes accumulated in deeper water and above the bottom of organic matter. Based on the dynamics of changes in oxygen concentration in water in the vertical cross-section of the lake in 2008, it was estimated that in the period of 100 days (from the spring homothermy to the establishing of summer stagnation conditions), about 45,000 kg O_2 vanished from the metalimnion and hypolimnion. Scarce literature data concerning the pulverizing aerator with wind drive efficiency allow estimating that at optimal wind speed, during the whole day, it can maximally introduce about 20 kg of oxygen to water [21, 27]. In reality, such conditions only exist for a short period of the day, and the amount of oxygen introduced, in the case of such a large water basin, is definitely too small. This has been confirmed by the results obtained at a smaller lake – Resko Górne, where no improvement was stated after the period of 4-year operation of the device [28]. The low effectiveness of oxygenation of lakes by means of wind aeration results from low efficiency of the Savonius turbine [29]. It is also problematic that energetic potential of wind over the open surface of the lake is applied as the main criterion of selection of the method [30]. According to the designer, the best efficiency of the device is obtained at a wind velocity of 3-5 $m \cdot s^{-1}$, irrespective of direction. The Savonius turbine uses wind from any direction. Our field observations showed that the turbine does not operate in the case of occurrence over the lake of wind swirls resulting from increased friction against terrain around the lake or on the lake (islands). Due to this, the criterion of selection of the wind aeration method must be exposure of the lake to wind, particularly from the direction dominating in the summer season. Studies on Lake Góreckie revealed that the aerator efficiency during the summer is very low (in July and August during the day the turbine turned sporadically). The obstacle is the shape of the lake (two basins: southern and northwestern), a forested island in the middle of the lake's length, location of the lake in a depression, and morphology of its vicinity. Moreover, the lake is situated crosswise to the western direction from which frequency and velocity of winds over Poland is the highest [31]. The number and height variety of natural terrain cover reduces the strength and flow of winds over the lake. In the aerator zone on Lake Góreckie, flow of wind is not free for the majority of directions, and particularly for winds of the western sector. This results in low efficiency of the aerator's operation. Due to the complicated character of the issue, the problem mentioned will constitute the subject of a separate paper.

Conclusions

1. In the first year of the Lake Góreckie restoration, the improvement of water transparency was observed only at the end of summer. The increase in water transparency did not cause the improvement of water oxygenation. In the summer period, the lake was deoxygenated from a depth of 4 m on average, and hydrogen sulphide occurred from a depth of 10 m.
2. In the first year of aerating the hypolimnion water by means of the wind aerator, no visible effects of its operation occurred. They were not observed even in the direct vicinity of the aerator. During the study, the aerator turbine very often was not in operation, or turned with a minimum rate, which did not result in water oxygenation.
3. The chemistry of lake water in 2010 was similar to 2008. A direct, but short-term effect of precipitation of phosphates with the application of a iron coagulant was low phosphate concentrations.

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