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Proposal for Water Quality Improvement by Using an Innovative and Comprehensive Restoration Method

Jolanta Grochowska

Department of Water Protection Engineering and Environmental Microbiology, Institute of Engineering and Environmental Protection, Faculty of Geoengineering, University of Warmia and Mazury in Olsztyn, Prawocheńskiego St. 1, 10-720 Olsztyn, Poland; jgroch@uwm.edu.pl

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Abstract: This study was conducted on Miłkowskie Lake (23.7 ha; 15.0 m) in the context of implementing new restoration methods for improving the water quality. The study found that the nutrient loads introduced into the lake from catchment are higher than the critical concentrations for the ecosystem. This indicates the need to cut off or at least reduce the main sources of pollution. The primary production in the lake is extremely large: oxygen saturation of the surface water above 200%, pH value of 9.44, chlorophyll a content of 70.98 mg m^{-3}, and a low visibility of 0.5 m. The most important step in maintaining good lake quality will be to redirect waters of the main inflows SI-1 and SI-2 to the hypolimnion zone by pipelines. A complementary method for discharging the polluted water to the hypolimnion zone will be the phosphorus inactivation method by using iron and aluminum coagulants. After the application of spring doses of coagulants, an anti-cyanobacterial preparation will be introduced into the water in the "active bottom" zone, and then bioremediation by a microbiological probiotic preparation will be applied to the sediment in the same zone. A new complex protection and restoration method should be supported in the form of biomanipulation.

Keywords: water quality; lake pollution; comprehensive lake restoration

1. Introduction

Fresh water pollution due to the discharge of untreated communal and rain effluents into bodies of water is a major global problem. Anthropo-pressure gives rise to water pollution by introducing various types of substances or waste into bodies of water [1,2]. The most common types of polluting substances include pathogenic organisms, oxygen-demanding organic substances, and inorganic and organic toxic substances. The introduction of raw and improperly treated wastewater into lakes causes ecosystem degradation [3,4]. On the one hand, this can introduce toxic substances that cause the death of aquatic organisms; on the other hand, it brings a high load of organic matter that immediately mineralizes and completely depletes the oxygen in the water, which causes the death of fish and other oxygen-breathing organisms. In addition, nutrients introduced with sewage occur in high concentrations and in a form readily assimilated by primary producers. Under natural conditions, the aquatic vegetation and algae development, constituting primary production, is regulated by the shortage of one of the chemical components or by a particular system of physical or hydro-chemical conditions of the water environment. This is a specific mechanism of self-regulation of aquatic ecosystems [5–7]. Excessive nutrient load contributes to the violation of the existing balance and increases, at least in the initial phase, the intensity of primary production. Clear growth of organic matter usually leads to disturbances of oxygen settings and sometimes even to complete deoxidation of the environment due to the consumption of oxygen in the decomposition of organic matter. The appearance of oxygen losses in water over-bottom sediment during stagnation periods leads to a reduction of the redox potential and consequently to the release of reduced ions from sediments into the near bottom water.

In this situation, bottom sediments cease to be a nutrient trap, and, in particular, a trap for phosphorus, the most important factor causing eutrophication [8,9].

The change in the lake phytocenosis structure, characterized by an increase in the proportion of cyanobacteria, which are invasive and highly toxic organisms, is listed among the unfavorable symptoms of a high trophic status of water reservoirs [10]. Other negative phenomena follow: change in the water's color, smell and taste, low transparency, over-oxygenation of the surface water layer, anaerobic conditions in the bottom layer of water, and appearance of hydrogen sulfide. Sometimes water, especially that of urban lakes, can be an epidemiological threat for bathers, resulting from the presence of pathogenic bacteria in the gastrointestinal tract (mainly of the *Salmonella* genus).

The rapid acceleration of lake water degradation, which is related to anthropo-pressure, has forced the search for effective methods for inhibiting or reversing this process and its adverse consequences. To improve the quality of lake water in Poland and around the world, restoration treatments (technical and biological) have been developed, which cause permanent nutrient immobilization in the sediments or the removal of the excess beyond a lake ecosystem [11–17]. For improvement of the ecological state of water, it is essential to limit the importation of pollutants from the catchment. The monitoring of sewage management in the reservoir basin should occur, followed by making an inventory and calculating the balance of pollutants originating from point, area emission and atmospheric sources. Then it is important to determine the pollution load which could be allowed to enter a lake [18,19].

The elimination of point sources (domestic and industrial sewage and storm water carried to either the lake or its tributaries through water collectors) is a fundamental step in any lake protection program. Pollution from spatial sources is mainly caused by agricultural activity and therefore can be controlled through a variety of methods adjusted to particular catchments. All approaches aim at closing the circulation of water and nutrients within an area dedicated to agricultural production and limiting their transfer to adjacent land. What is particularly important for the protection of bodies of water is proper land management in the immediate surroundings of lakes and rivers.

At present, it is necessary to combine several methods in order to halt the process of the rapid degradation of lakes. Removing the external load of pollution can improve water quality in moderately eutrophied lakes only. In degraded reservoirs, where bottom sediments have become a secondary source of water pollution, protective measures are insufficient. In this case, it is necessary to design an effective restoration method.

The objective of this research project was to develop an innovative concept of restoration measure that would improve the water quality of the strongly degraded Miłkowskie Lake (Masurian Lake District, Poland). A new concept for a lake restoration solution has been developed, in which the technical method (pipelines introducing surface water to the bottom of the lake) was combined with biological (mineralizing bacteria) and chemical (phosphorus inactivation) methods based on the current trophic status of the lake and its external loading.

Before the implementation of the proposed restoration methods, which will be carried out in the lake basin, it is necessary to apply protective measures. They will consist in the modernization of the Sewage Treatment Plant in the village of Miłki and the construction of an open channel, the bottom of which can be lined with sorption material (expanded clay) covered with hydrophilic plants.

2. Materials and Methods

2.1. Study Site

Miłkowskie Lake lies in the drainage basin of the rivers Pisa, Narew and Vistula and belongs to the macro-region known as the Masurian Lake District [20]. This is a glacial lake, presenting characteristics of a ribbon lake. The longer axis runs from the northwest to the southeast (NW-SE). Morphologically, this is a single-basin lake with a distinguishable sink basin. The maximum depth of 15.0 m occurs in the central part of the lake (Figure 1). More detailed morphometric parameters of the lake are given in Table 1.

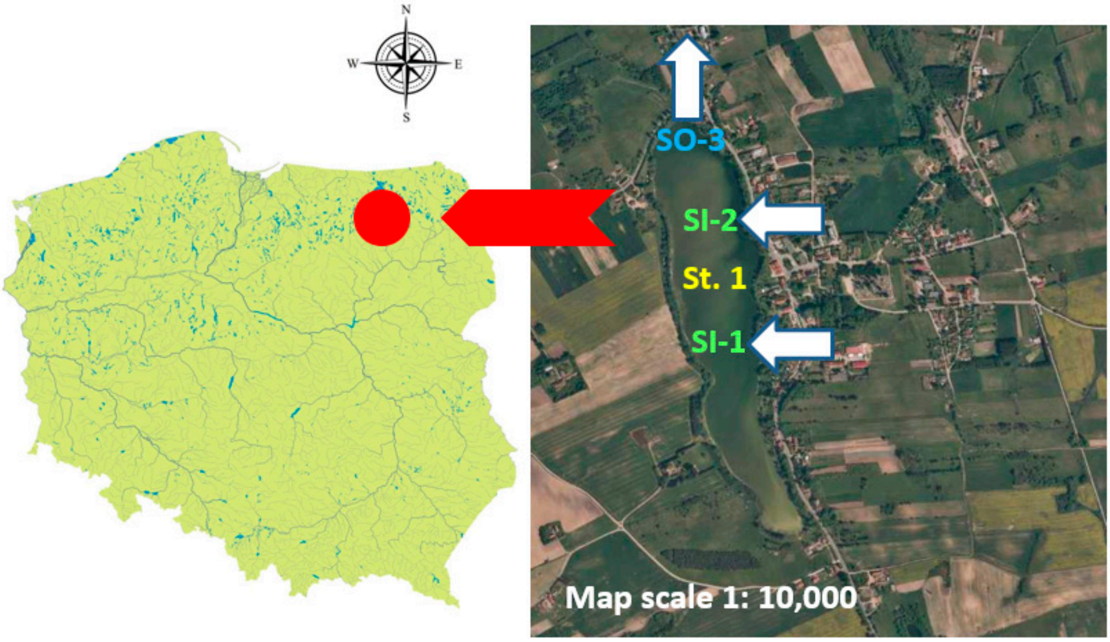


Figure 1. Miłkowskie Lake's location and the site of water sample collection.

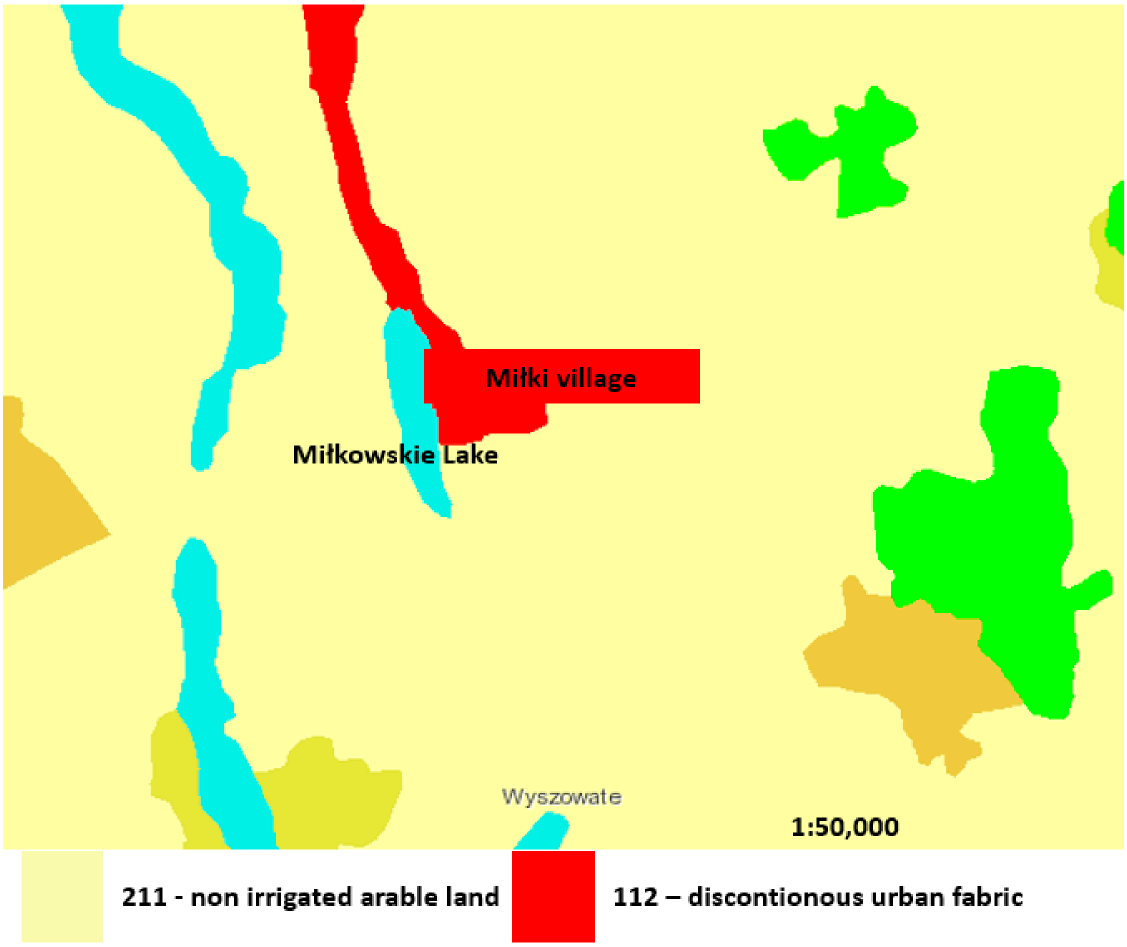
Table 1. Morphometric parameters of Miłkowskie Lake. (Inland Fisheries Institute in Olsztyn, 1975).

Parameter	Value
Geographical coordinates	53°5′65″ N 21°5′25″ E
Elevation of average water table (m AMSL)	124.8
Lake surface (ha)	23.7
Maximum depth (m)	15.0
Average depth (m)	5.3
Relative depth	0.031
Depth indicator	0.28
Volume (in thousand m^3)	982.3
Maximum length (m)	1300.0
Maximum width (m)	275.0
Average width (m)	182.3
Elongation indicator	4.7
Coastline length (m)	2850.0
Shoreline expansion indicator	1.6

The total catchment basin of Miłkowskie Lake covers 5.30 km^2 and is clearly divided into two areas: a smaller western (1.14 km^2) area with a strongly agricultural character, with a small number of buildings and other forms of land use, and a larger (4.12 km^2) eastern area with a more diverse range of development forms, occupied by buildings, arable lands, grassland and wasteland. Both of these areas are characterized by a slightly undulated surface structure (average slopes of 2.9 and 2.1%, respectively), conducive to the transfer of pollutants to the lake, and an extensive drainage network, which also accelerates the migration of biogenic pollutants into the water receiver. Both areas are dominated by arable land (western part 80.0% of the area, eastern part 62.0% of the area) (Table 2). Until the end of the 1990s, Miłkowskie Lake was a receiver of dairy sewage (Figure 2).

Table 2. Types of land use in the total catchment of Miłkowskie Lake.

Land Use	Total Catchment (5.3 km^2)	
	East Part (113.5 ha)	**West Part (412.4 ha)**
Arable lands	90.98 (ha)	255.83 (ha)
Meadows and pastures	3.88 (ha)	20.05 (ha)
Barren lands	10.92 (ha)	75.95 (ha)
Forests	3.29 (ha)	17.52 (ha)
Built-up lands	4.48 (ha)	43.05 (ha)



https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=mapview

Figure 2. Forms of land cover in the catchment area of Miłkowskie Lake.

2.2. Water Sample Collection

The physicochemical properties of Miłkowskie Lake water were determined in an annual cycle, taking into account the vegetation season (April 2018, June 2018, August 2018, and October 2018). Samples were taken from the surface and bottom water layers at one station located in the central, deepest place of Miłkowskie Lake (ST-1). In addition, in November 2017, March 2018, May 2018, June 2018, August 2018, and October 2018, measurements of the hydro-chemical parameters of the water in the surface inflows and outflow were performed (Figure 1). There were three sampling sites, and their detailed characteristics are as follows:

Site 1 (SI-1)—drainage tributary (northeastern shore of the lake)

Site 2 (SI-2)—"eastern watercourse" flowing into Miłkowskie Lake. This watercourse drains an area of approximately 3.2 km^2, and it is heavily transformed by anthropo-pressure: urbanized area

(Miłki village), arable fields, meadows and pastures, and sewage inflow. The average water flow value was 10.4 L s^{-1}.
Site 3 (SO-3)—outflow from the lake toward Wojnowo Lake

The results from 1982 (April 1982, June 1982, August 1982, and October 1982) were taken from the archives of the Department of Water Protection Engineering and Environmental Microbiology.

2.3. Water Sample Analysis

The scope of water analysis included the following: temperature and oxygen profiles (every 1 m of depth), pH and conductivity (YSI 6600 V2), total phosphorus, orthophosphate, ammonium and nitrate [21] total nitrogen (Shimadzu TOC/TN5000 analyzer, Kyoto, Japan), chlorophyll a (colorimetric method after concentration on a Whatman GF/B glass fiber filter and extracted with acetone; Nanocolor UV/VIS, Macherey-Nagel; 750/664 nm before and 750/665 after acidification), water transparency with Secchi disc (SD), and seston by gravimetric methods after filtration on a Whatman GF/C glass fiber filter. Every analysis was performed in triplicate. The coefficient of variation (CV) for the repeated analysis was 2% [22]. Flow velocity measurements were performed by using a VALEPORT (801 model) electromagnetic flowmeter and determining the water discharge by using Harlacher's method [23]. The results of total phosphorus (TP), total nitrogen (TN) and SD were statistically analyzed (one-way ANOVA, $p = 0.05$, Tukey's HSD) using a Statistica 13.0 software package [24]. An alternative hypothesis tested was the presence of significant differences in mean annual values of nutrients between the year 1982 (inflow of domestic and dairy sewage) and the year 2018 (indirect inflow of domestic sewage). The trophic state indices (TSI_{TP}, TSI_{TN}, TSI_{SD}, and TSI_{CHL}) were calculated based on the concentrations of total phosphorus, total nitrogen, and chlorophyll a as well as the Secchi disc visibility [25,26].

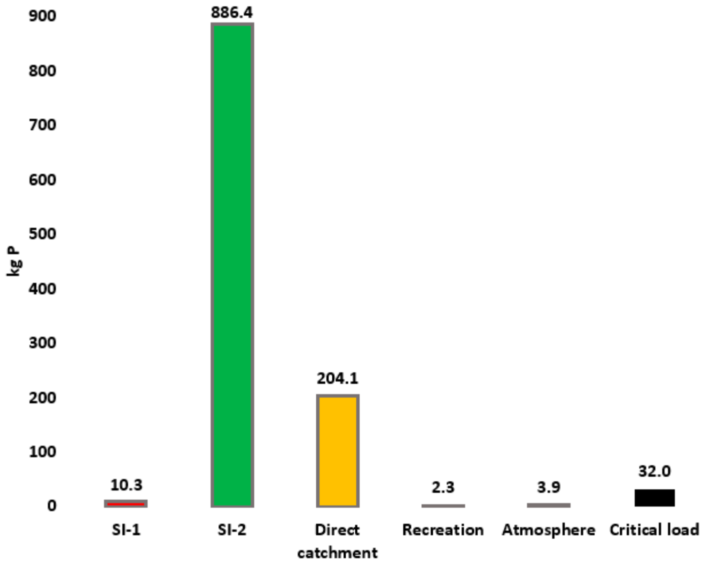
2.4. Nutrient Load Calculation

Nutrient loads at the individual stations were calculated as the product of the volumetric water discharge and the concentration of a nutrient in water. Nutrient loads were calculated with the generally accepted time periods method. The external load of the lake with nutrients originating from surface runoff (direct catchment area) was calculated with a method that is recommended and applied by OECD (*Organisation for Economic Co-operation and Development*) [27]. This method consists of calculating the loads with flow coefficients [28], which depend on the method of land management, land use and the difference in land elevation over a given area. The nutrient load introduced into a given lake by precipitation was determined based on the coefficients of pollution deposition per surface unit (the lake, in this case) [29]. Pollutants originating from the recreational use of Miłkowskie Lake were excluded from consideration because the poor quality of the lake's water prohibits swimming and bathing. The permissible (so-called critical) and dangerous phosphorus loadings were calculated according to the static model of Vollenweider [30] because the outflow from the lake is episodic.

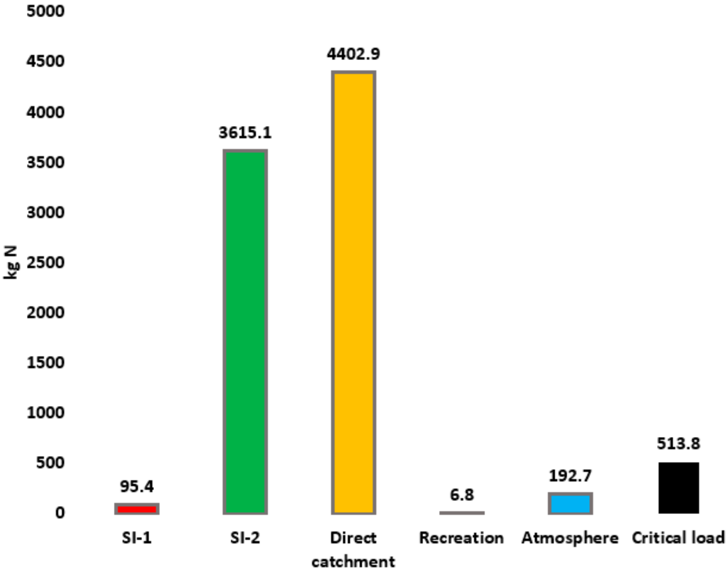
3. Results

3.1. Load of Nutrients

The total annual load of nutrients reaching Miłkowskie Lake are 1107.0 kg P and 8312.8 kg N, which, when converted to the lake's surface area, corresponds to 4.7 g P m^{-2} $year^{-1}$ and 35.1 g N m^{-2} $year^{-1}$. The most important sources of phosphorus and nitrogen were the "eastern watercourse" and surface runoff from arable land, which supplied 886 kg P $year^{-1}$, 3615 kg N $year^{-1}$ and 139 kg P $year^{-1}$, 3468 kg N $year^{-1}$, respectively (Figure 3a,b).



(**a**)



(**b**)

Figure 3. (**a**) Annual (2018) load of phosphorus (kg P) entering Miłkowskie Lake from different sources and dangerous load. (**b**) Annual (2018) load of nitrogen (kg N) entering Miłkowskie Lake from different sources and dangerous load.

The remaining effluents were responsible for the total load of 81.9 kg of phosphorus and 1229.6 kg of nitrogen imported into the lake annually. The actual phosphorus load of Miłkowskie Lake is over 34-fold higher than the critical load for the ecosystem (32.0 kg P year^{-1}), and the actual nitrogen load for the analyzed reservoir is over 16-fold higher than the critical load (513.8 kg N year^{-1}) (Figure 3a,b). This calculation indicated that lake restoration must be preceded by removing the main sources of pollution.

3.2. Lake Water Hydrochemistry

Measurements of Miłkowskie Lake's thermal profiles, morphometrical properties and theoretical range of water mixing (3.9 m) derived from the Patalas equation [31], which exceeds the thickness of the epilimnion during summer stagnation (3.0 m), thus classifying the lake as bradimictic, i.e., as a reservoir with impeded circulation of water mass. In the spring period, the water temperature in the 3-m-thick layer changed slightly: from 19.4 to 18.5 °C (Figure 4). At a depth of 4 m, a temperature of 13.1 °C was noted, and the thermal gradient between 3 and 4 m was 5.4 °C m^{-1}. The metalimnion layer held up to 6 m. Below that, the water temperature dropped gently and was 5.6 °C at the bottom. At the end of the summer stagnation, the epilimnion waters were heated to 22 °C. A thermocline with a maximum gradient of 3.4 °C m^{-1} between 2 and 8 m deep. The bottom layer of water had a temperature of 5.9 °C. In autumn, at the end of November, full homothermia was not found. The temperature of the water layers with a thickness of 9 m oscillated near 8.8 °C and deeper temperature was 6.3 °C (Figure 4). Lake Miłkowskie is not well exposed to wind because it extends from northwest to southeast, which is not in line with the prevailing winds in Poland (predominance of winds with SW and W directions). In addition, the edges of the lake are quite steep, overgrown with trees, and built-up from the east, which additionally hinders wind access.

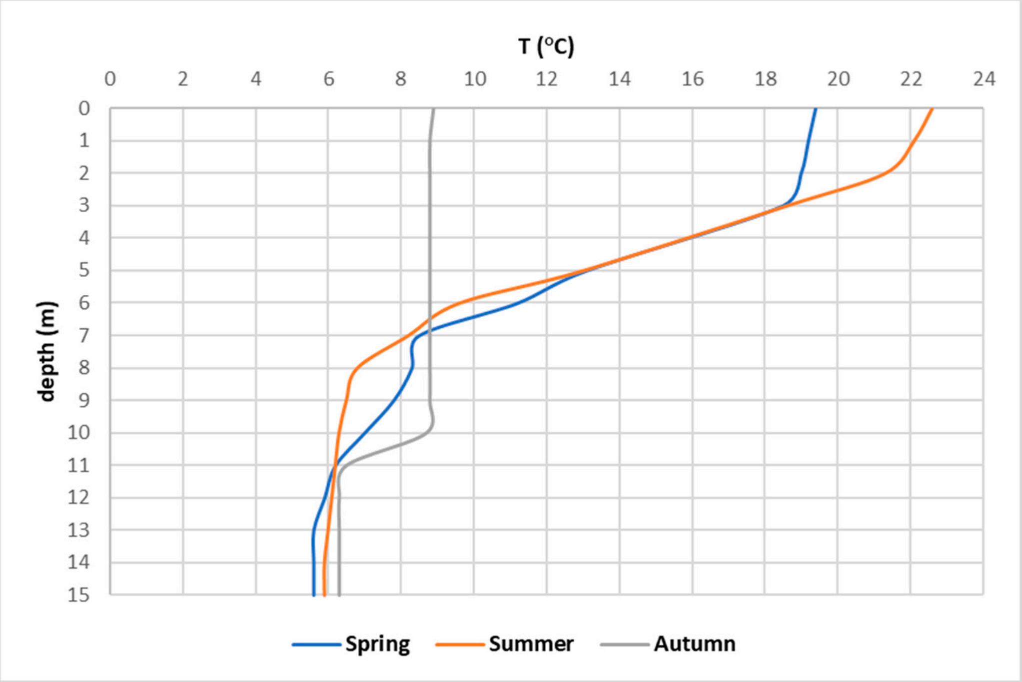


Figure 4. Annual (2018) thermal settings in Miłkowskie Lake.

The oxygen conditions in Miłkowskie Lake depended on the water mass dynamics and the degree of pollution of the lake. Only the surface layers were characterized by high oxygenation (often above 200% saturation) (Figure 5). A sharp oxycline was present between the depths of 3 and 4 m, leading to complete oxygen depletion in the water below 8 m. During no complete autumn homothermia did oxygen conditions improve significantly. In the water layer up to 9 m deep, oxygenation varied between 49.2 and 41.3% saturation (from 5.7 to 4.8 mg O_2 L^{-1}), while below that depth the oxygen concentration dropped sharply, and from 12 m to the bottom anaerobic conditions were noted (Figure 5).

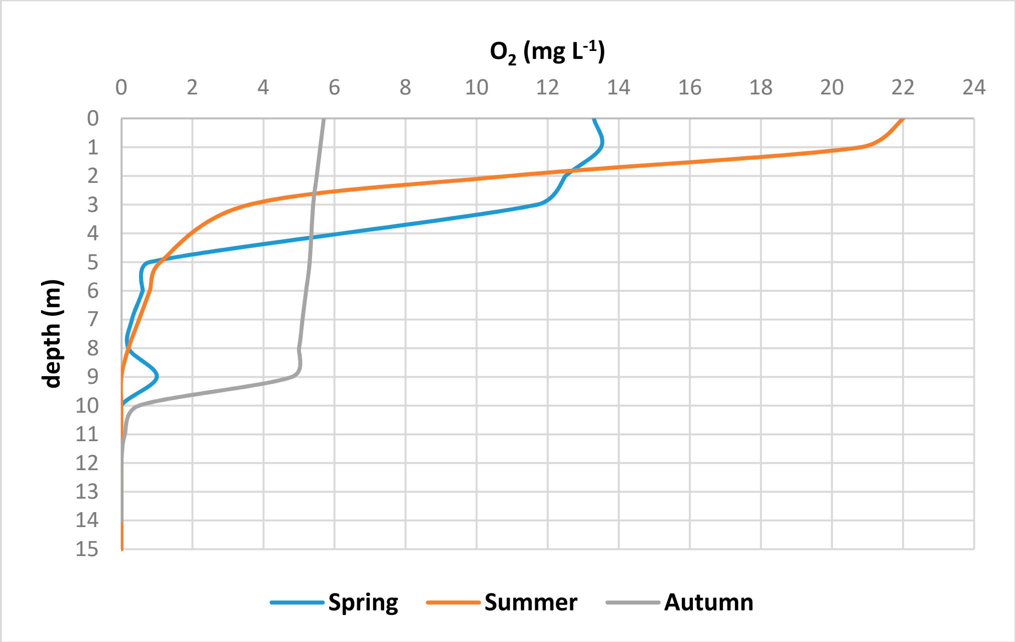


Figure 5. Annual (2018) oxygen settings in Miłkowskie Lake.

Anaerobic conditions in the bottom layer indicate the possibility of internal fertilization from bottom sediments, which was confirmed by the results of research of the bottom sediment and interstitial water of Miłkowskie Lake.

The basic nutrient elements for the aquatic environment are phosphorus and nitrogen compounds. The rate of eutrophication and, consequently, the quality of the water in the lake depends on their quantity and availability. Miłkowskie Lake belongs to reservoirs rich in these compounds. A statistical analysis was carried out to examine the differences in the contents of total phosphorus and total nitrogen in Miłkowskie Lake, when the reservoir was a receiver of dairy sewage, and currently when the inflow of pollution takes place via tributary SI-2.

The statistical analysis did not reveal any differences between 1982 (during the inflow of dairy sewage) and 2018 (indirect inflow of domestic sewage) (Table 3) with regards to the content of total phosphorus in the surface water layers of Miłkowskie Lake. In 1982, during the inflow of dairy sewage, the average concentration of TP (±SD) in the surface water layer was 0.324 ± 0.079 mg P L^{-1}, while that in 2018 was 0.348 ± 0.115 mg P L^{-1} (Figure 6).

Table 3. Results of one-way ANOVA analyses (with Tukey HSD) for the investigated variables in Miłkowskie Lake water.

Variable	between 1982 and 2018	
	F Value	***p* Value**
Total phosphorus surface water	0.22280	0.644190
Total phosphorus near-bottom water	14.45490	0.001943
Total nitrogen surface water	9.721609	0.007558
Total nitrogen near-bottom water	2.035660	0.175567
Secchi disc visibility	1.426937	0.252111

The statistical analysis of the results showed that cutting off dairy sewage discharge caused a significant change in the total nitrogen content in the surface water of Miłkowskie Lake and did not cause a significant change in the nitrogen content in the near-bottom water layer of the analyzed lake (Table 3). In 1982 (inflow of dairy sewage), the total nitrogen throughout the water column of Miłkowskie Lake varied in the range of 1.80 to 18.70 mg N L^{-1}, and its average value fluctuated near

5.72 mg N L^{-1} (±4.34) (Figure 7). In 2018, in the entire water volume of Miłkowskie Lake, the total nitrogen content changed between 1.14 and 9.50 mg N L^{-1} (mean value oscillated near 3.75 mg N L^{-1}, ±2.64) (Figure 7).

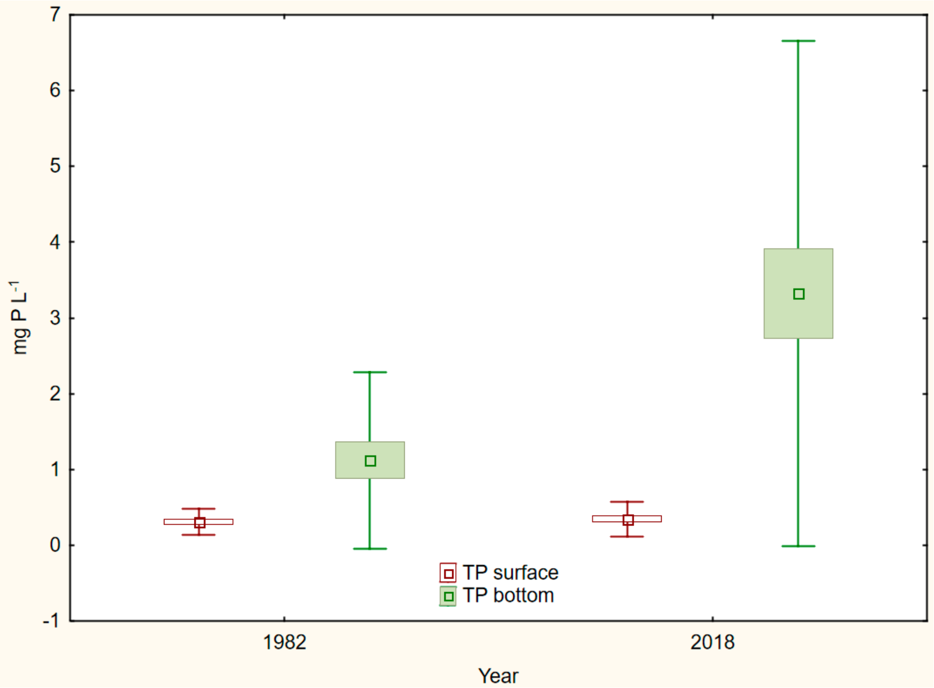


Figure 6. Mean annual (1982 and 2018) values of the total phosphorus content (±SD) in the water of Miłkowskie Lake.

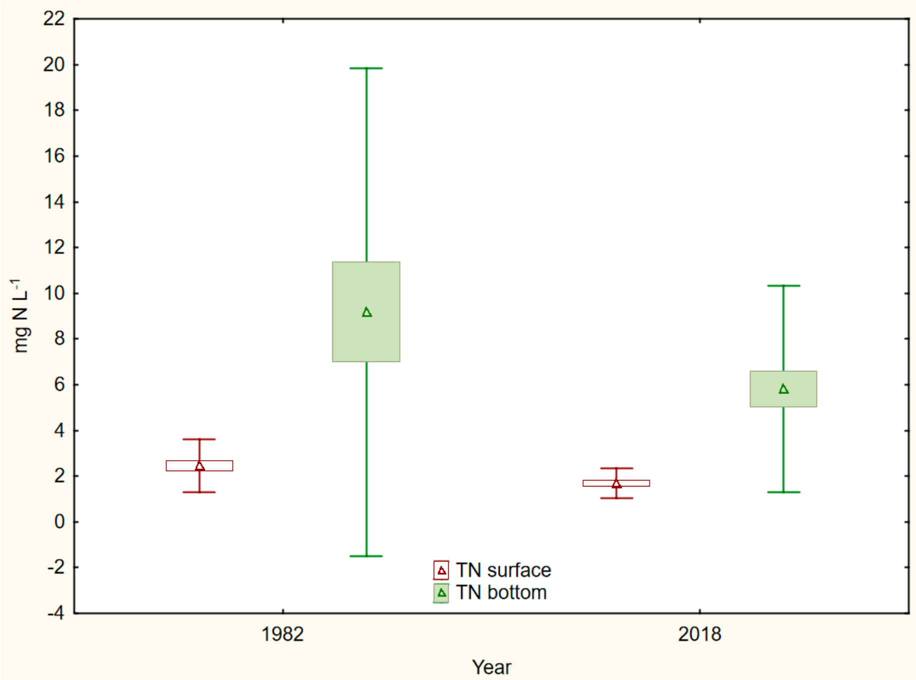


Figure 7. Mean annual (1982 and 2018) values of the total nitrogen content (±SD) in the water of Miłkowskie Lake.

The ratio used for forecasting undesirable cyanobacterial blooms is the TN/TP ratio. Values of this ratio in the range from 5 to 10 indicate a high probability of mass development of cyanobacteria.

In Miłkowskie Lake, this ratio ranged from 4 to 7, which, at a relatively high water temperature and due to its slightly alkaline reaction, indicates the presence of optimal conditions for the appearance of undesirable blooms of cyanobacteria in the lake.

The statistical analysis of the results showed that between the analyzed research years, Miłkowskie Lake did not see significant differences in the Secchi disc visibility (Figure 8). In 1982 (inflow of dairy sewage), the average value of water transparency measured as the Secchi disc visibility was 1.50 m (±0.78), and in 2018 it was 0.90 m (±0.25).

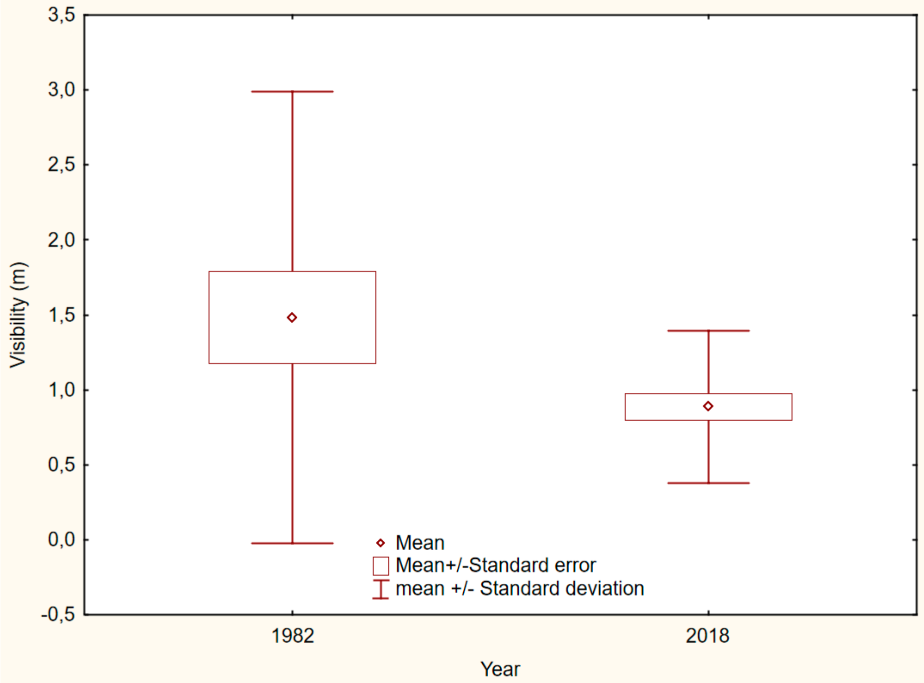


Figure 8. Mean annual (1982 and 2018) values of the Secchi disc visibility (±SD) in the water of Miłkowskie Lake.

The hypertrophic state of the water of Miłkowskie Lake is also confirmed by the international OECD classification [27]. The values of every parameter (concentration of total phosphorus, concentration of chlorophyll a, and visibility) demonstrated strong pollution of the analyzed lake (Table 4). Analysis of the TSI point scale showed that Miłkowskie Lake should be classified as a hypertrophic water body. Partial TSI values were in the characteristic range for hypertrophy, and only TSI_{TN} was in the upper eutrophic range (Table 5).

Table 4. Classification of water trophies of Miłkowskie Lake based on the 2018 results (OECD 1982).

Parameter	Oligotrophy	Mezotrophy	Eutrophy	Hypertrophy	Miłkowskie Lake	Trophy
TP (μg P L^{-1})	<10	10–35	35–100	>100	362	Hypertrophy
Chlorophyll a (μg L^{-1})	<2.5	2.5–8.0	8–25	>25	67	Hypertrophy
Visibility (m)	>6	6–3	3–1.5	<1.5	0.9	Hypertrophy

The high degree of pollution is also indicated by the high calcium content, varying from 37.1 to 90.7 mg Ca L^{-1} (Table 6) and corresponding to values typical for contaminated reservoirs (>35 mg Ca L^{-1}).

Table 5. The trophic status index (TSI) calculated for Miłkowskie Lake on the basis of the visibility (SD), chlorophyll concentration (Chl), total phosphorus (TP) and total nitrogen (TN) in 2018.

Index	Value
TSI_{TP}	84
TSI_{TN}	64
TSI_{SD}	70
TSI_{Chl}	74

(Oligotrophy TSI < 40 Mezotrophy TSI 40–50, Eutrophy TSI 50–70 Hypertrophy TSI > 70).

Table 6. Annual (2018) variability of the physicochemical parameters in the surface and bottom water layers of Miłkowskie Lake.

Parameter	Unit	Surface Min-Max/Average/SD	Bottom Min-Max/Average/SD
Reaction	pH	7.60–9.44/8.58/0.775	7.02–7.41/7.28/0.176
Conductivity	$\mu S\ cm^{-1}$	318–480/380/73	598–666/630/31
Orthophosphate	$mg\ P\ L^{-1}$	0.026–0.104/0.137/0.169	0.632–2.450/1.549/0.758
Ammonium	$mg\ N\ L^{-1}$	0.04–1.13/0.41/052	1.87–8.25/5.38/2.73
Nitrate	$mg\ N\ L^{-1}$	0.094–0.151/0.114/0.036	0.040–0.140/0.094/0.041
Calcium	$mg\ Ca\ L^{-1}$	37.1–66.4/48.8/14.3	82.8–90.7/87.0/3.3
Chlorophyll a	$mg\ m^{-3}$	30.31–70.98/54.61/18.40	
Seston	$mg\ L^{-1}$	12.5–24.4/18.2/4.8	

Additionally, the observed values of the electrolytic conductivity and chlorides pointed to mineral water pollution. In eutrophic reservoirs, conductivity values are in the range of 200 to 400 $\mu S\ cm^{-1}$, while the conductivity of the waters of Miłkowskie Lake varied in the range of 318 to 666 $\mu S\ cm^{-1}$ (Table 6). According to Grochowska et al. [7], water that is not receiving pollutants contains a maximum of 15 $mg\ Cl\ L^{-1}$ (Table 6). The chloride content in the water of the studied lake exceeded the above range several times and varied from 32 to 58 $mg\ Cl\ L^{-1}$.

3.3. Phytoplankton

The phycological analysis of the waters of the Miłkowskie Lake [32] showed little variety in species composition with the simultaneous intensive development of phytoplankton. Lake phytoplankton were characterized by a definite dominance of cyanobacteria. In the 0–2 m layer, *Cyanophyceae* formed a biomass of 27.4 $mg\ L^{-1}$, which accounted for 87.5% of total phytoplankton biomass. Cyanobacteria biomass in the 3–8 m layer was definitely smaller and amounted to 9.6 $mg\ L^{-1}$, but the share in total biomass was still large at 76.2%. In both layers, species of the genus *Microcystis* belonging to *Chroococcales* occurred in the largest number. The dominant was *Microcystis ichthyoblabe*, and the subdominant was *Microcystis botrys*. *Microcystis Wesenbergii* was also present. Threadworms from *Oscillatoriales*, *Planktothrix agardhii* and *Planktolyngbya limnetica*, were occasionally found. Blooming amounts of *Cyanophyceae* were accompanied by *Dinophyceae*. These had an 11.5% share in total phytoplankton biomass in the 0–2 m layer, and 19% in the 3–8 m layer. Their biomass was 3.6 $mg\ L^{-1}$ and 2.4 $mg\ L^{-1}$, respectively. It was composed of the species *Ceratium furcoides* and *Peridinium villei*. There was a small share of *Chlorophyta* phytoplankton, 1% in the 0–2 m layer and 4.8% in the 3–8 m layer. Green algae formed 0.3–0.6 $mg\ L^{-1}$ biomass. The most abundant (especially in the 3–8 m layer) species was *Phacotus lenticularis*. *Chlorophyta* was also represented by species of the genera *Pediastrum* and *Desmodesmus*. There were no representatives of other systematic algae groups in the phytoplankton.

4. Discussion

Miłkowskie Lake is a strongly degraded reservoir, in which the mechanism of water being supplied with nutrients from the bottom sediments is activated as a result of many years of industrial and municipal sewage discharge. Currently, the main sources of phosphorus compounds in the lake are the drainage water supply (SI-1) and the watercourse from the east (SI-2), to which sewage from the inefficient wastewater treatment plant (WWTP) in Miłki is discharged. Comprehensive restoration treatments will therefore focus on seasonal elimination of these nutrient sources.

In order to reduce the external load of nutrients from agricultural land, an open channel, about 1500 m long and 5 m wide, should be built along the western shore of Miłkowskie Lake. The bottom of the channel should be lined with sorption material covered with hydrophilic plants.

The aboveground parts of hydrophilic plants assimilate biogenic elements and increase aesthetic value [33]. In turn, the underground parts of plants (rhizomes and roots) release oxygen into the rhizosphere, which supports the processes of biodegradation of organic matter and nitrification, as well as biogenic substances. The plants which will be planted in the open channel of the west shore of Miłkowskie Lake are *Glyceria maxima*, *Phalaris arundinacea* and *Phragmites australis*. Applying all of the aforementioned solutions will result in a reduction of the external load from direct catchment of the lake by approximately 80%.

The sorption material proposed for laying in the open channel is expanded clay. It is an artificial, highly porous aggregate made of thermally treated mineral resources (mainly clay and loam). The expanded clay grains have evenly distributed fine internal closed pores, the diameter of which usually does not exceed 1.0–1.5 mm. Recently, expanded clay is more often used in wastewater treatment systems—as a filling of beds, as biological filters (biofilters), and as reactors with a fluidized and a suspended or movable bed [34]. According to various researchers, the phosphorus adsorption capacity for expanded clay is from several hundred mg P to 12 g P per 1 kg of product [35]. In sewage management, phosphorus removal efficiency of 85–95% is usually reported for solutions based on ground filters.

The next important step is the modernization of the Sewage Treatment Plant in Miłki village. In addition to improving the efficiency of nutrient removal in the biological section, this should be treated with the third level of treatment, i.e., a coagulant should be applied to reduce phosphorus by almost 95%. New biological section technology will remove nitrogen at the level of 80%.

At the same time, pipelines should be built to carry the waters of the SI-1 and SI-2 tributary to the tropholitic zone of Miłkowskie Lake.

To achieve this goal, the water of the main inflow (SI-2) and drainage water (SI-1) will be redirected to the lake hypolimnion zone. The water of these tributaries must be directed to hypolimnetic waters to eliminate the load when they enter the trophogenic (production) zone. This treatment will limit phytoplankton (especially cyanobacterial) blooms. In addition, diverting well oxygenated watercourses into the bottom zone of Miłkowskie Lake will contribute to improving the oxygen conditions in hypolimnion. Solim and Wanganeo [36] reported that in good oxygen there is precipitation and binding of phosphorus in bottom sediments, and the nitrification of ammonia nitrogen formed during the mineralization of organic matter can also occur. By improving oxygen conditions in the near-bottom layer of Miłkowskie Lake, the release of phosphorus and ammonium from bottom sediment will be stopped, and, consequently, their concentrations in the entire volume of water will be reduced. In addition, improved oxygen conditions at the bottom water layers will cause an immediate reduction in the amount of ammonia due to its oxidation to nitrate nitrogen. Nitrate nitrogen produced in the process of nitrification passed into the bottom sediment, and a denitrification process occurred there [37]. The product of denitrification was molecular nitrogen, which was released into the atmosphere.

A complementary method for discharging the most pollution-charged water to the hypolimnetic zone will be the phosphorus inactivation method. This is a procedure involving the precipitation of phosphorus from the water column and its permanent immobilization in the bottom sediments of the lake. In this way, the amount of total biogenic elements in the lake's water volume and that involved in the circulation of matter in water is reduced. This method limits the development of phytoplankton, and a smaller amount of suspended matter improves the water transparency.

After the application of spring doses of iron and aluminum coagulants, bioremediation preparation will be applied to the sediments in the "active zone" (this is a microbiological probiotic preparation containing selected strains of microorganisms, whose high metabolic activity begins accelerated mineralization of organic matter). Phosphates released through the action of probiotics will be precipitated and immobilized in bottom sediments with the help of subsequent autumn doses of coagulants.

4.1. The Reduction in External Sources of Pollution Improves the Oxygen Conditions in the Near-Bottom Water Layer and Reduces the Availability of Nutrients in the Production Zone

The water of surface tributaries (SI-1 and SI-2) will be redirected to the bottom zone of the lake in the vicinity of the deepest place in the lake ecosystem by pipelines, ensuring its oxygenation. The method of lake restoration by controlling the selective outflow of water has been known in the literature for over 60 years, although there are still few examples of its practical application. Poland is a country where this solution was first used on Kortowskie Lake [38]. In 1956, the natural outflow from this lake was blocked by weir, which allowed water to be accumulated to a depth of approximately 0.5 m, and overfertilized hypolimnion waters were drained through a pipeline laid on bottom sediments. Lake restoration by the method of selective withdrawal of hypolimnetic water was used on several lakes in North America and Europe, including five lakes currently in Poland [39].

The positive effects of this method are the gradual reduction of the nutrient pool and organic matter accumulated in the lake basin.

The solution adopted in this concept also includes the selective direction of water through the pipelines but in the opposite direction. As mentioned earlier, the introduction of surface tributary waters into the deep lake is intended to temporarily cut off the load of biogenic pollutants (nitrogen and phosphorus) introduced with the inflow water from the trophogenic (production) zone. This solution makes it possible to limit the availability of nutrients for primary producers during the growing season. The oxygenation of bottom waters with oxygen introduced by the waters of the SI-1 and SI-2 inflows will be an additional aspect.

4.1.1. Redirecting the Inflow Waters at SI-1

The pipeline via which tributary SI-1 water will be redirected to enter the bottom of the lake will be made of plastic in the form of reinforced InCor (SN8) DN160 external sewer system pipes in the initial section (7 m), which is exposed to damage (ice cover movements, animals, and third parties); the remainder (73 m) will be made of smooth PVC-U pipes (Figure 9). The pipeline will be linearly loaded by means of steel angles and fastened with steel tape every three linear meters. Such a solution simultaneously strengthens and stiffens the pipeline structure as well as protects against uncontrolled pipe expansion. Immediately, at the end of the last section of the pipeline, a support plate should be anchored in the bottom to protect the pipeline intake from falling into bottom sediment. For the expected construction of the pipeline, a panel with minimum dimensions of 2.5 × 2.5 m should be made of plastic, while maintaining a specific weight that prevents the panel from flowing out. For the purposes of the pipeline operation at the SI-1 inflow, it is necessary to place a DN600 drainage well on the shore of the lake, to which the DN150 filling pipeline will be connected from the water side and the SI-1 inflow will be connected from the land side. The height difference of the bottom of the outlet kinetics in relation to the ordinate of the water table is 0.3 m. This is a sufficient fall to obtain the right amount of damming in the well to overcome the linear resistance inside the pipeline. It has been calculated that, with a relatively small calculation flow of 5 L s^{-1}, the required damming is only 0.06 m. With the existing slope of the backwater stream, the range is negligible (<1 m). Research shows that flows in this watercourse only incidentally approach the computational flow, while its average value oscillates by approximately 1–2 L s^{-1}, which indicates that on average the water will pile up to a height of 0.02 m.

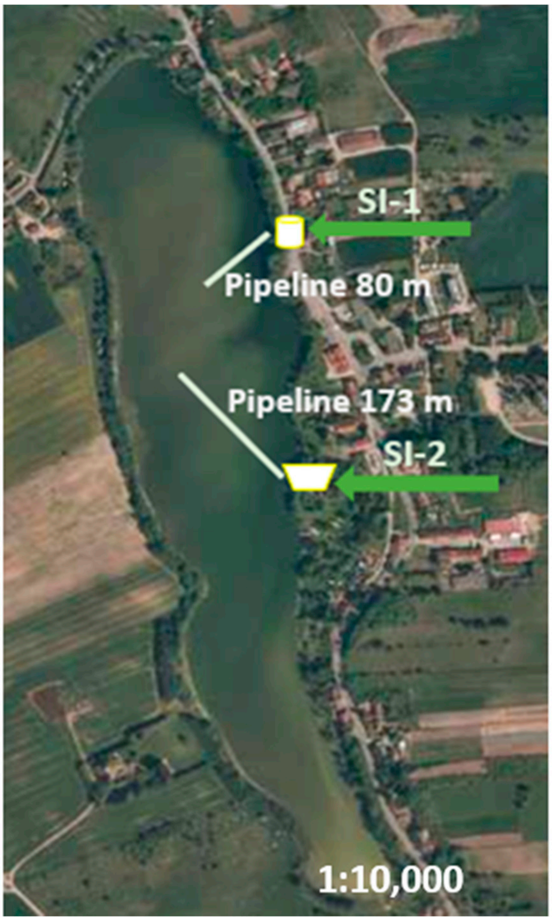


Figure 9. Scheme of siting of the pipelines for the oxygenation of Miłkowskie Lake.

4.1.2. Redirecting the Inflow Waters at SI-2

The pipeline by which tributary SI-2 water will be redirected to enter the bottom of the lake will be made of plastic in the form of reinforced InCor (SN8) DN160 external sewer system pipes in the initial section (14 m), which is exposed to damage; the remainder (159 m) will be made of smooth PVC-U pipes (Figure 8). This change is dictated by the need for the most effective cooling of relatively warm summer water carried by the watercourse and directed into the pipeline. The smaller the temperature difference between the water fed through the pipeline and the naturally cool bottom water of the lake, the more favorable the oxygenation of the deepest part of the lake. The pipeline will be linearly loaded by means of steel angles and fastened with steel tape every three linear meters. Such a solution simultaneously strengthens and stiffens the pipeline structure as well as protects against uncontrolled pipe expansion. Immediately at the end of the last section of the pipeline, a support plate should be anchored in the bottom to protect the pipeline intake from falling into bottom sediment. For the expected construction of the pipeline, a panel with minimum dimensions of 2.0 × 3.5 m should be made of plastic, while maintaining a specific weight that prevents the panel from flowing out. The pipeline for diverting water from the SI-2 watercourse to the bottom of Lake Miłkowskie was designed on the basis of the volume of required water flow, the adopted water damming height in the watercourse on the dam, the degree of filling and the speed of water flow in the pipeline, taking into account hydraulic losses. As determined during the research, 20 L s^{-1} was assumed to be the calculated flow.

Based on calculations, it was found that, for the DN250 pipeline diameter and its length of 173 m, the required damming to achieve the design flow is 0.18 m. During periods when this flow will be greater than 20 L s^{-1}, the damming height will increase automatically. In a hypothetical situation of achieving critical flow (for the designed system, this is approximately 22 L s^{-1}), damming on the valve will reach the upper allowed ordinate (124.9 m above sea level), and further excess water will overflow through the highest dams of the valve and flow into the lake in a traditional way, i.e. surfactant. During most of the year, there are flows much lower than the calculated flow in the watercourse; hence, the average damming height at the facility will only be approximately 0.1 m.

Each water structure located in the watercourse causes water to accumulate, which moves up the stream creating a so-called accumulation curve. At a certain distance, the free surface gently connects to the surface of the non-accumulated water, determining the so-called backwater range, which is a measure of the building's impact on the hydrological relationships of the watercourse. In practice, backward reach is most often determined by Tolkmidt's calculation methods. The maximum backflow range generated by damming water through the SI-2 watercourse will be 46 m. The valve plate will allow periodic cleaning of the system from silt. A grille is provided to protect the pipeline inlet against foreign objects. Additionally, the inlet of the pipeline will be equipped with a bolt made of stainless steel boards enabling flow blocking.

4.2. Reduction of Internal Sources of Pollution

The main goal of every restoration method is to reduce the phosphorus content in water down to a level that can limit primary production. Some quantity of the P is removed from the water column due to accumulation in organisms and sedimentation. Sediments act as a nutrient trap until sorption capacity is exhausted. In hypertrophic lakes with oxygen depletion in the near-bottom zone, sediments are a significant phosphorus source and become the cause of secondary pollution [40]. The prolonged use of Miłkowskie Lake as a wastewater receiver led to a high concentration of phosphorus in the lake water (more than 5 mg P L^{-1}) as well as in the sediment [41]. High phosphorus concentrations in the lake water persisted after the dairy sewage flow was stopped, which was due to permanent anoxia of the over-bottom water and consequently limited ability of the sediment to bind P. In the anoxic hypolimnion, 30% of the P can form complexes with iron, and another 30% can be incorporated into the phytoplankton biomass, while the remaining phosphorus is dissolved in water. Phosphates released by desorption and during organic matter decomposition in the bottom sediments have diffused toward the over-bottom water layer, and later to the trophogenic layer as a result of vertical transport [42–44]. In Miłkowskie Lake, despite high primary production (strong oxygen oversaturation in water, high pH, low water transparency, and high organic matter content), the total depletion of mineral phosphorus in the water was noted at the end of summer stagnation. this indicates that the constant loading exists from the drainage basin or from the shallow epilimnetic sediments rich in phosphorus. Over 40% of the lake's bottom has contact with the epilimnetic zone and may play an important role in nutrient loading. Although the extent of release from the bottom sediment under aerobic conditions is generally lower than under anaerobic ones [45–47], nutrients are introduced directly into the trophogenic zone, where they are used by phytoplankton [48].

The use of pipelines introducing SI-1 and SI-2 inflows into the bottom zone of the lake will reduce the amount of phosphorus in the surface water layer and at the same time improve the oxygenation of the bottom water layer. In addition, due to improved oxygenation of the over-bottom water, the release of mineral phosphorus from sediment will be inhibited and, consequently, the mineral P concentration will also be decreased in over-bottom water.

The improvement of near-bottom water oxygen conditions in Miłkowskie Lake as a result of surface tributary waters (SI-1 and SI-2) introduced into the bottom zone will be of a local nature. To achieve a clear improvement in the water of the reservoir, it will be necessary to use an additional method of re-cultivation: phosphorus inactivation. Phosphorus inactivation is usually carried out using aluminum or iron compounds, while calcium compounds are used less often. At present, the most popular are aqueous solutions of aluminum coagulants PAX and iron coagulants PIX. Aluminum is an element forming a solid connection with phosphorus even in anaerobic conditions, and it has a low oxidation-reduction potential. However, in some water environment conditions, there is potential toxicity of dissolved aluminum forms [49]. Numerous studies have shown that at a pH typical of most waters (6–8) the composition of aluminum coagulants is dominated by insoluble polymeric $Al(OH)_3$, which does not threaten water organisms. Iron compounds are not toxic to hydro-bionts, but anoxic conditions in bottom water lead to their destabilization and the dissociation of iron-phosphorus bonds, which considerably limits the effectiveness of lake restoration. Based on the experience and research results obtained by the Department of Water Protection Engineering and Environmental Microbiology in the field of lake re-cultivation by phosphorus inactivation [50,51], and on the physicochemical properties of the water of Miłkowskie Lake, two types of coagulants will be dosed: PAX 18 and PIX 111. Appropriate doses of coagulants introduced into the lake water will bind the mineral phosphorus present in the water column as well as the precipitating mineral and organic suspension to the bottom sediments. Coagulant flocs settle on the surface of bottom sediments, permanently immobilizing phosphorus precipitated from the water column and creating isolation for phosphates, which are released from bottom sediments.

After constructing two filling pipelines eliminating the impact of the most important sources of lake pollution, SI-1 and SI-2, the phosphorus inactivation treatments will be carried out (twice a year, in spring and autumn, in two consecutive years). The doses of PIX and PAX coagulants were determined on the basis of the phosphorus fractions in the interstitial water and bottom sediments and the amount of natural components in sediments having sorption capacity in relation to phosphorus, such as Al, Fe, and Ca [52,53].

The calculated doses of aluminum coagulant for Miłkowskie Lake are as follows: the demand for profundal sediment for aluminum is 3719.0 kg Al, and the demand for aluminum with which to bind phosphorus in the water column in the central zone is 5621.0 kg.

The dose of iron coagulant for Miłkowske Lake is as follows: the demand for littoral deposits for iron is 9.081 kg Fe and the demand for iron for binding phosphorus in the water depth in the coastal zone is 8.554 kg.

4.3. Bioremediation

In the coastal zone of the Miłkowskie Lake, where the bottom sediments are well oxygenated, waters will be applied for the bioremediation process. This process involves the introduction of bacterial strains in the form of tablets, which accelerates the process of mineralization accumulated at the bottom of organic matter. Phosphates released in this process will be precipitated from the water column and blocked in bottom sediments with the help of autumn doses of coagulants.

According to the distributor of the microbiological preparation for the microbiological bioremediation of pollutants accumulated in the bottom sediment of the lake, a dose of 5 tablets per 100 m^2 of sediment is needed (5 tablets corresponds to the weight of 0.5 kg of the microbiological probiotic). Taking into account the surface of the active bottom, where the water above the bottom is oxygenated, i.e., to a depth of 2.5 m (anaerobic conditions prevail, which do not favor the aerobic mineralization of pollutants using probiotics containing strains of aerobic bacteria), which is 71,000 m^2, the dose of preparation necessary for the bioremediation of sediment is 355 kg. It is proposed to dispense the substance once a month during the two-year reclamation period in the period June–August (a total of six dosages). The dose introduced into the sediment during one application is 59 kg.

4.4. Biomanipulation

For maintaining the positive effects of re-cultivation in Miłkowskie Lake, rational fishery management should be implemented. This method can be applied through the use of biomanipulation, which involves the conscious shaping of the biocenosis of aquatic organisms by changing the species composition of ichthyofauna. The main goal of biomanipulation is to increase the number of large forms of zooplankton, mainly *Cladocera*, and through their feeding to control the amount of phytoplankton, which are the first link in the trophic pyramid, thus reducing water bloom phenomenon. To achieve this effect, it is necessary to limit the number of sedentary fish such as bleak, sun-bleak, small perch, juvenile roach, silverfish, bream, and crucian, which feed on zooplankton or seek food in bottom sediment. The reduction of these fish assemblies can be achieved through selective harvesting (without the use of towed tools). According to Gołdyn [54], the recommended amount of recessed fry is at least 1000 pieces/ha, and the restocking material should have a size exceeding 10 cm because at this stage of development the pike is going to feed on other fish.

Miłkowskie Lake, according to the records in the fisheries report, is regularly stocked with pike in the amount of 100 kg autumn fry, zander in the amount of 20,000 summer fry and eel in the amount of 20 kg stocking fry. Two of the abovementioned species are obligatory predators.

5. Conclusions

The implementation of restoration methods should be proceeded by eliminating the external load of pollutants from the catchment area. The main step to maintaining good quality of the water of Miłkowskie Lake will be to redirect waters of the inflows SI-1 and SI-2 to the hypolimnion zone by pipelines. The waters of these tributaries must be directed to hypolimnetic water to eliminate the load with which they enter into the trophogenic (production) zone. This treatment will limit phytoplankton (especially cyanobacteria) blooms. In addition, diverting well oxygenated watercourses into the bottom zone of Miłkowskie Lake will contribute to improving the oxygen conditions in hypolimnion.

A complementary method for discharging the most polluted water to the hypolimnetic zone will be the phosphorus inactivation method. This is a procedure involving the precipitation of phosphorus from the water column and its permanent immobilization in the bottom sediments of the lake. In this way, the amount of total biogenic element amount in the lake's water volume and in the circulation of matter in water is reduced. This solution limits the development of phytoplankton, and a smaller amount of suspension improves the water transparency.

After the application of spring doses of iron and aluminum coagulants, bioremediation by a microbiological probiotic preparation will be applied to the sediment in the same zone. That preparation contains selected strains of microorganisms, whose high metabolic activity begins accelerating mineralization of organic matter. Phosphates released through the action of probiotics will be precipitated and immobilized in bottom sediments with the help of subsequent autumn doses of coagulants.

A new complex protection and re-cultivation method should be supported in the form of biomanipulation.

Taking into account an interesting summary of actions to improve the quality of Delavan Lake waters [55], Table 7 was prepared containing a brief description of all proposed methods and the expected percentage of pollution reduction.

Table 7. Summary of protective and restoration activities for Miłkowskie Lake.

Actual Sources of Nutrients	Phosphorus kg P Year^{-1}	Nitrogen kg N Year^{-1}
Atmosphere	3.9	192.7
SI-1	10.3	95.4
SI-2	886.4	3615.1
Direct catchment	204.0	4402.9
Recreation	2.3	6.8
Total loading	1106.9	8312.9
Critical load according to Vollenweider [30]	32.0 kg P year^{-1}	513.8 kg N year^{-1}
Impact of protective measures on the reduction of the external load of phosphorus and nitrogen		
1. Open channel with sorption material and hydrophilic plants—west shore of the Miłkowskie Lake		
Approximate percent reduction of pollution from direct catchment—0% of nutrients load Cost—25,000$	Reduced load of phosphorus 40.9 kg P year^{-1}	Reduced load of nitrogen 880.6 kg N year^{-1}

Table 7. *Cont.*

Actual Sources of Nutrients	Phosphorus kg P Year^{-1}	Nitrogen kg N Year^{-1}
2. Modernization of the Sewage Treatment Plant in Miłki village		
Approximate percent reduction of pollution from SI-2—95% of phosphorus load and 80% of nitrogen load Cost—300,000$	Reduced load of phosphorus 44.3 kg P year^{-1}	Reduced load of nitrogen 723.0 kg N year^{-1}
3. Construction of pipelines directing the waters of the SI-1 and SI-2 surface tributaries towards the waters of the hypolimnion. Pipeline outlet 2 m above the bottom.		
Approximate percentage reduction of pollution from SI-1 and SI-2 (after modernization of Sewage Treatment Plant in Miłki village)—50% of nutrients load Cost—35,000$	Reduced load of phosphorus from SI-1 5.2	Reduced load of nitrogen from SI-1 47.7
	Reduced load of phosphorus From SI-2 22.1	Reduced load of nitrogen from SI-2 361.5
Total load of nutrients introduced into the lake after protective measures	74.4 kg P year^{-1}	489.3 kg N year^{-1}
Impact of restoration techniques on the reduction of the amount of nutrients in the water column		
1. Phosphorus inactivation—I stage, spring Approximate percentage reduction of amount of phosphorus in water column—50% Cost—20,000$		
2. Application of probiotic preparation (summer—first stage) Approximate percentage reduction of amount of phosphorus and nitrogen in water column—0%, only mineralization of organic matter Cost—100,000$		
3. Biomanipulation—I stage Introduction of predatory fish to eliminate planktivorous fish Cost—33,000$		
4. Phosphorus inactivation—II stage, spring Approximate percentage reduction of amount of phosphorus in water column—50% Cost—20,000$		
Stages 1, 2, 3 of restoration treatment will be repeated in the next year		

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