Impact of Limited Water Flow in a Pipeline on the Thermal and Oxygen Conditions in a Lake Restored by Hypolimnetic Withdrawal Method

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Abstract

Lake Kortowskie was studied during water stagnation, when it is subjected to bottom water withdrawal to outflow through a pipeline. The examinations were carried out after flow reduction from 0.25 $m^3 \cdot s^{-1}$ to about 0.05 $m^3 \cdot s^{-1}$. It has been revealed that hypolimnion withdrawal has much more effect on the temperature and oxygen content in the water body. Destruction of the thermal settings and the rate of oxygen depletion occurs with variable intensity, depending on the amount of water withdrawn by the pipeline. In the period of limited hypolimnion withdrawal the temperature increase near the bottom was slower (by 0.2°C on average in 10 days) than in the period of the pipeline's maximal capacity (i.e. 0.5-0.8°C).

Keywords: lake, restored, hypolimnetic withdrawal, temperature, oxygen

Introduction

Eutrophication, which is based on an increase of abundance and rate of organic matter production resulting from enhanced input of nutrients from allochthonous and autochthonous sources, contributes to disturbances in self-regulation mechanisms in aquatic ecosystems. A rough answer to the question about what type of trophic state are we dealing with might be an analysis of oxygen settings, as the presence or absence of this element in the water is the motor for many processes occurring in lakes. To a high degree, it determines the chemical properties of water through oxidation and reduction processes. Oxygen depletion in water overlying the bottom sediments in stagnation periods results in reduction of the redox potential and in consequence - in release of the reduced ions from the sediments to water [1, 2]. Moreover, it contributes to upkeep of biological diversity and abundance [15, 17]. The importance of oxygen in lakes was seemingly best presented by Hutchinson in the following sentence: "to classify or to understand a lake, one must know its oxygen regime in space and time" [9].

Factors having an effect on the amount of dissolved oxygen in water include the lake's morphometry and amount of organic matter in the lake. An additional element in the case of Lake Kortowskie is removal of bottom water from the southern part of the lake by means of a pipeline. This intervention comprises a method of recultivation, aimed at halting eutrophication and improve the trophic state of the lake. The primary assumption of the experiment was to obtain homothermy in summer and, eventually - oxygenation of the whole water body. Unfortunately, even only momentary breaks in circulation of the considerably heated (16-17°C) water body had caused rapid oxygen depletion in the process of intensive degradation of the organic compounds in the water and on the surface of bottom sediments [19]. Therefore, the essence of the method has become removal of the bottom water not only in summer but also in winter. During both stagnation periods the bottom collected products of organic matter break-down that have been deposited on the sediment surface or settle from the trophogenic layer. Removal directly to outflow of water abundant in nutritious substances, eliminates high quantities of nitrogen and phosphorus [7].

Hypolimnetic withdrawal as a recultivation method may not be used in any way. One of the conditions for its effectiveness is to maintain thermal stability of the lake. Increase of the water outflow through forced hypolimnion withdrawal during the minimal water-inflow, occurring in the hydrological year during summer stagnation, may lead to the following:

- disturbances of the thermal settings and intensive heating up of the bottom water layers, and in consequence - an increase of organic matter mineralisation rate and accelerated oxygen depletion,
- disadvantageous nutrients balance in a lake, resulting from a decrease or total cease of flow in the pipeline, in the peak of nutrients release from the sediments (second half of summer stagnation),
- negative influence on the lake's littoral, as a result of the lowered water table,
- increase of underground and surface water drainage from the lake's watershed and thus of pollutant load.

Having in mind the factors resulting from the disturbance in the thermal settings, the aim of the present study was to determine the impact of a limited hypolimnion withdrawal on the thermal and oxygen settings in the water of Lake Kortowskie. The results of the survey have been compared with the effects obtained at max. flow in the pipeline.

Material and Methods

The object of the examinations was Lake Kortowskie of 89.7 ha surface area, 5.3 Mm^3 water volume, 17.2 m max. depth, and 5.9 m mean depth. The lake is situated in the Mazurian Lakeland and belongs to the group of so-called "olsztyńskie" lakes [20, 24].

The lake is fed by 5 inflows and the surface area of the direct drainage basin is 102.1 ha [14]. On the southern side of the lake the Kortówka River flows out. At this point, in the frame of the experiment conducted in 1956, a weir was posted that enables to cut down the surface outflow and remove the hypolimnion water through a pipeline. In 1956-1974 for bottom water removal a wooden pipeline

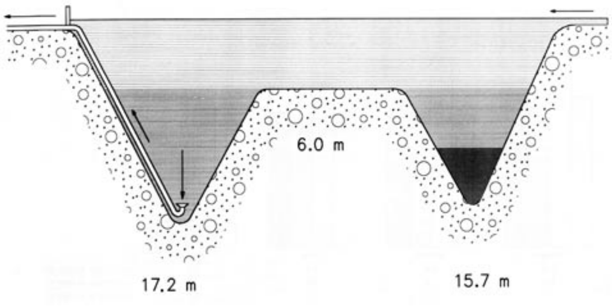

Fig. 1. Scheme of the "Kortowski experiment".

was used, and since 1976 until present the operating pipeline is made of glass fibre and polyester resins. Its length equals 250 m, diameter 600 mm, and the max. capacity at the high permitted water table of 103.2 m above sea level is 0.25 $m^3 \cdot s^{-1}$ (Fig.1).

The gate on the outflow from the lake facilitates regulation of the amount of water flowing in the pipeline, therefore in order to carry out the project in years 1990-1994 the flow rate was diminished from the max. of 0.25 $m^3 \cdot s^{-1}$ to about 0.05 $m^3 \cdot s^{-1}$.

Water samples for analyses were taken on two posts situated at the two deepest points in the northern and southern part of Lake Kortowskie. The southern post (post S) due to the direct withdrawal of the bottom water by the pipe from this part of the lake is often called experimental. The northern post (post N) is treated as a reference due to the flat platform (6 m deep) dividing hypolimnion of the two parts during summer stagnation.

Temperature and oxygen were determined at distances of 1 meter during the stagnations and 2 meters during the turnovers. Water for analyses was sampled with a Ruttner's apparatus with a built-in mercurial thermometer (0.2°C accuracy of measurement). DO was determined using Winkler's method. In the discussion further on, the results of the 1986-1989 investigations have been used, when the flow in the pipeline equalled 0.25 $m^3 \cdot s^{-1}$ [6].

Results and Discussion

Water Temperature

In summer months lakes of the temperate zone are characteristic of a vertical thermal stratification. The epilimnion range depends mainly on a lake's exposure to wind activity [18]. This depth, calculated from Patalas' equation [21], takes in case of Lake Kortowskie the value of 5 m. In years 1990-1994, in the peak of summer stagnation (i.e. second half of August) the thickness of the epilimnion equalled usually 7 m and was similar to the values determined in 1952-1975 (i.e. 6-8 m) [11].

The mean thickness of the epilimnion overlaps with the depth of the middle part of Lake Kortowskie (6 m), dividing the two basins, thus in summer only the epilimnion waters are easily mixed in the whole lake. The hypolimnion water deposited underneath that depth, in both parts of the lake are isolated and do not mix with each other. This allows comparisons between the pipeline's effects in the southern part and the settings in the northern part.

Water temperature in the layer of 0-7 m in the examined period did not vary considerably from that determined in Lake Kortowskie in previous years. Nor were the differences between the two parts of the lake detected. The max. temperatures of the surface water layers during the summer stagnation in years 1990-1994 in the whole lake ranged from 20.3 to 27.7°C. From the above, it can be concluded that the pipeline's operation has no direct effect on the epilimnion's temperature in the examined lake.

Table 1. Mean temperatures and oxygen concentrations at 10 m depth and near the bottom (15 m post S and 13 m post N) in summer months of 1990-1994.

MONTHS	SOUTHERN POST		NORTHERN POST	
	temp. [°C]	O_2 [mg/dm^3]	temp. [°C]	O_2 [mg/dm^3]
	10 meters		10 meters	
June	10	1.82	9.5	1.3
July	11.3	0.58	10.4	0.54
August	12.9	0.94	11.1	0.46
September	14	4.52	12.3	2.72
	15 meters		13 meters	
June	7.9	0.9	8	0.6
July	9.1	0.42	8.6	0.24
August	9.9	0.2	9.1	0.14
September	10.3	0.82	9.4	0.98

The direct effects of the applied recultivation method were observed during summer stagnation in the water layer beneath 7 m, in the experimental part.

In years 1990-1994 water temperature from June till August was increasing in the southern part by 2°C near the bottom and by 2.9°C at 10 m, on the average. In the northern part, the temperature was rising much slower, i.e. by 1.1°C and 1.6°C respectively (Tab. 1). With regard to the rate of the temperature increase it has been revealed that during the limited hypolimnion withdrawal the temperature was increasing near the bottom in the southern part by 0.2°C on the average during 10 days. Mientki has reported [11] that at the max. flow in the pipeline such increase was more intense, as in 1976-1982 it amounted to 0.5-0.8°C during 10 days. The cited values clearly point out that the disturbance to the natural thermal settings, resulting from the hypolimnion withdrawal, occurs with various intensity, depending on the amount of water withdrawn by the pipeline (Fig. 2).

At the limited hypolimnetic withdrawal lower heating of the bottom water in the experimental part as compared to the period when the pipeline was operated with max. capacity was observed. A consequence of smaller intervention in the thermal settings was the extension of summer stagnation. In 1990-1994 the summer thermal stratification was maintained for 181 days in the southern part and for 171 days in the northern part, and was similar to that in 1952-1954 and 1974-1975, when the pipeline was not used [11]. In 1986-1989 (pipeline capacity 0.25 $m^3 \cdot s^{-1}$) the max. duration of the summer stagnation was shorter than in the experimental part by 5 weeks, and in the reference part by 2 weeks [6].

Durability of the thermal settings exhibited by the stability of the water body is directly related to a lake's exposure to wind activity. The additional causative factor in the case of Lake Kortowskie is hypolimnetic withdrawal. Temperature increase in the bottom water caused by the pipeline's operation results in a diminishment of the temperature difference between the surface and the bottom water layers, and ultimately the thermal settings become less stable. At the limited hypolimnion withdrawal, the heating of the bottom water in the southern part was minimal and in consequence - the water body was more stable as in the years when the pipeline was not operating (in 1953 about 180 $J \cdot m^{-2}$ on post S and 115 $J \cdot m^{-2}$ on post N) [11]. In 1990-1994 the maximal stability of the water body was contained in the range of 148.9-275.9 $J \cdot m^{-2}$ in the experimental part and 98.5-193.4 $J \cdot m^{-2}$ in the reference part. In the period when the pipeline was operated with 0.25 $m^3 \cdot s^{-1}$ capacity, the max. values amounted to (respectively) 112.3-173.1 and 90.3-112.2 $J \cdot m^{-2}$ [6].

In the second half of summer much importance was gained by convection currents. The effect of their activity is epilimnion deepening. The size of that phenomenon is growing as a result of hypolimnetic withdrawal in the southern part. The cold bottom water removed through the pipeline is replaced by warmer water comprising first the upper hypolimnion or the metalimnion. Equalisation of the water temperature near the bottom with that of the surface layers liquidates the thermal gradient and initiates autumn turnover.

The beginning of autumn turnover depends mainly on meteorological conditions in the given year, and in the southern part additionally on the amount of water withdrawn by the pipeline. In years when the surface water layers have higher temperature, liquidation of the thermal gradient occurs later. To obtain the above-described phenomenon different time is needed depending on water flow in the pipeline.

Water volume beneath 7 m comprises both the meta- and the hypolimnion. In the southern part of Lake Kortowskie it equals 409 thousand m^3. The calculated time

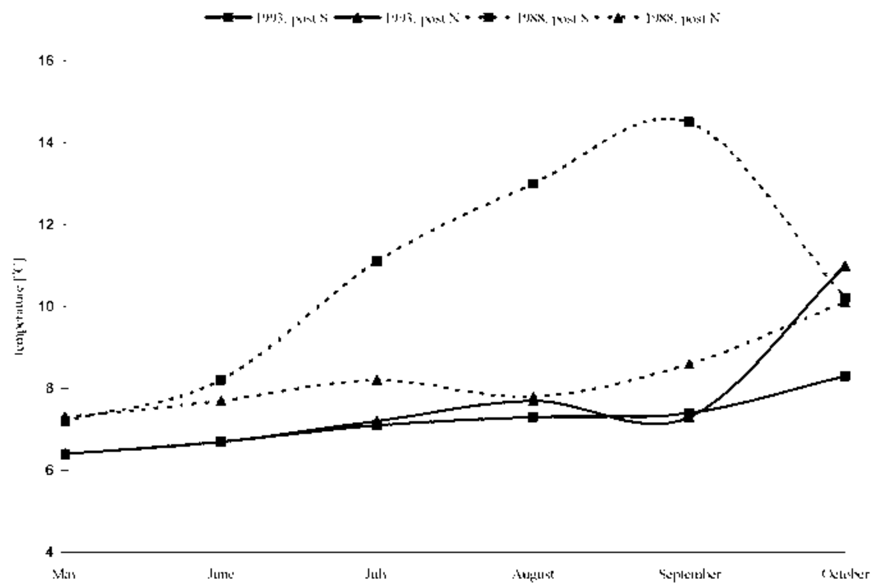

Fig. 2. Changes of the water temperature at the bottom (15 m post S and 13 m post N) in 1993 and 1988 in Lake Kortowskie.

needed to withdraw such an amount of water with the pipeline operating with 0.25 $m^3 \cdot s^{-1}$ capacity amounts to about 19 days, whereas at the limited flow of 0.05 $m^3 \cdot s^{-1}$ it is about 95 days. In both periods, depending on pipeline flow rate, after such time the homothermy in the lake was not observed. Autumn homothermy in 1990-1994 in the experimental part of the lake was observed in two years in September and in three years in October, whereas at the max. flow in the pipeline the same had been observed one month earlier [6].

Additionally, in the southern part of the lake, at the limited flow in the pipeline, the autumn turnover was initiated at the water temperature identical to or slightly higher than the northern part (post S: 7.4-13.1°C; post N: 9.2-14.1°C). At max. flow in the pipeline the temperature was much higher in the experimental part (post S: 14.4-17.5°C; post N: 12.2-13.2°C), [6].

Dissolved Oxygen in Water

Bottom water withdrawal has, as in the case of temperature, no direct effect on oxygen content in the epilimnion.

In the summer months of 1990-1994 considerable oversaturation with oxygen in the surface water layers was not observed. Oxygen saturation ranged from 95.3% to 123.9% in the southern part and from 92.8% to 112% in the northern part. Before the start-up of "Olszewski's pipeline" in 1956 and in the first years of the experiment the amount of oxygen at 1 m under the surface was very high. Maximal saturation with oxygen was determined in 1961 (221.8%) and in the following years the high values were observed sporadically (in 1981: 166.1%) [11]. Oversaturation with oxygen in the surface layers, very often sustained during the growing season, is typical for the eutrophic lakes [26]. Considerable decrease in oxygen content in the surface water in the past years, compared to the period before 1956, is an effect of the over 40-year recultivation of Lake Kortowskie and the gradual reduction of its eutrophication.

The amount of oxygen in the beginning of summer stagnation is determined by the duration of spring turnover. Prolonged spring turnover in Lake Kortowskie increases oxygen stock in the hypolimnion that in consequence shortens the period of anaerobic conditions at the bottom in the summer months [13]. An additional factor influencing oxygen settings in the upper and lower hypolimnion in the beginning of summer stagnation is the withdrawal of the bottom water with the pipeline to the outflow. In 1990-1994, in May (i.e. in the first month of the summer stagnation), mean oxygen concentration in the experimental part equalled 5.2 mg $O_2 \cdot dm^{-3}$ at 10 m depth and 4.9 mg $O_2 \cdot dm^{-3}$ near the bottom. A month later the oxygen amount decreased proportionally to values below 2 mg $O_2 \cdot dm^{-3}$ and 1 mg $O_2 \cdot dm^{-3}$, (Tab. 1).

In the first month of summer stagnation the daily mean oxygen consumption at 10 m depth amounted to 0.12 mg $O_2 \cdot dm^{-3}$, and 0.14-0.15 mg $O_2 \cdot dm^{-3}$ near the bottom. In the reference part, the values were, respectively, 0.2 mg $O_2 \cdot dm^{-3}$ and 0.13-0.14 mg $O_2 \cdot dm^{-3}$. At max. capacity of the pipeline (0.25 $m^3 \cdot s^{-1}$) oxygen consumption was more intensive in the upper hypolimnion (10 m) and amounted to 0.19 mg $O_2 \cdot dm^{-3}$ [6].

The reason for oxygen depletion in the summer months in the eutrophic lakes is utilisation for organic matter degradation and oxidation of the reduced substances both in the water body and on the bottom sediments surface. These processes are in the first row responsible for water deoxygenation at the interface with the bottom sediments in profundal [4] and subsequently in the whole hypolimnion.

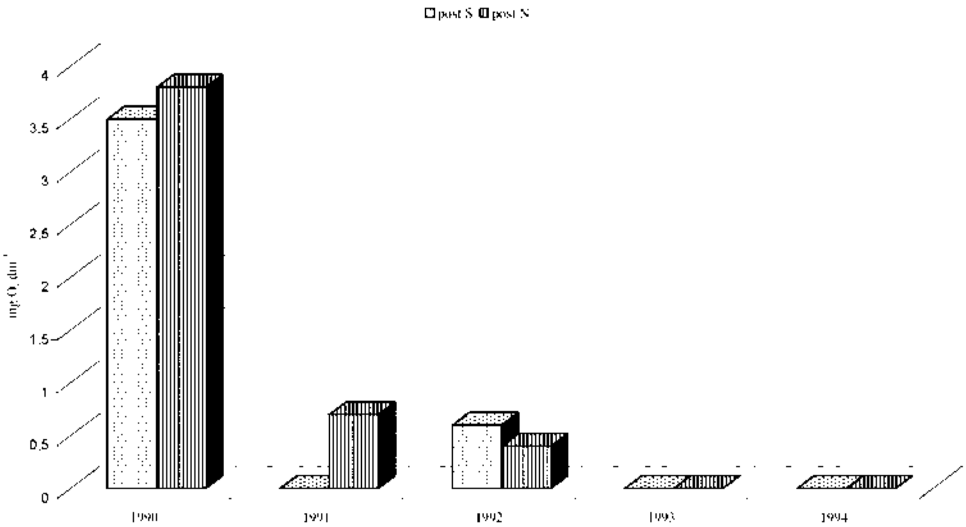

Fig. 3. Oxygen concentrations at the bottom (15 m post S and 13 m post N) in September in Lake Kortowskie, 1990-1994.

The rate of oxygen depletion in deeper water is an approximated indicator of the eutrophication advancement in a lake. Taking into account that during the summer stagnation of 1953 (before the recultivation) in both parts of Lake Kortowskie oxygen was not detected near the bottom yet in the end of May [19], in the last years of the 1st phase (1956-1973) in the second decade of June [11], and in the 2nd phase of recultivation (after 1976) only in July or August, it can be concluded that along with the years of the pipeline's operation, the eutrophication of the lake has been diminished. Shortening of the anaerobic conditions duration was observed also in the northern part, not directly subjected to recultivation which points at an indirect impact of the pipeline's operation on the whole lake.

Oxygen deficits in the bottom water during summer stagnation in the lakes recultivated with the hypolimnetic withdrawal method seem unavoidable. Oxygen depletion in the deeper water layers depends not only on the amount of organic matter but also on water temperature and morphometric properties of the hypolimnion [3, 5, 17]. It has been estimated that high temperature of the bottom water - the consequence of hypolimnetic withdrawal - increases oxygen depletion rate by 35% to 50% [10]. Pechlaner [22] has suggested that withdrawal of the oxygen-deficient bottom water and its replacement by water more abundant in this gas from the upper layers can compensate for oxygen consumption in the increased temperature but it does not actually improve the oxygen conditions at the bottom. Anaerobic hypolimnions is the feature of eutrophic lakes, thus lakes of little use for fisheries. With the described method a distinctive improvement cannot be expected and heating up of the bottom water only accelerates occurrence of oxygen deficits. Nonetheless, in Mientki's opinion [12] higher temperature and anaerobic conditions in the bottom water and at the surface of the bottom sediments are a positive phenomenon. In higher temperatures the intensity of organic matter mineralisation increases. In anaerobic conditions the mineral dissolved substances in the interstitial water are transported towards the surface of the sediments, and the reduction of the surface layer formed from iron oxides and hydroxides stimulates transport of ions to the near-bottom water. Their subsequent removal with a pipeline directly to the outflow results in sediment impoverishment, which in consequence will greatly diminish internal loading, and in a longer perspective may even eliminate it completely. It is especially important in the eutrophic lakes whose bottom sediments after cutting-down the external pollution sources become the main source of nutrients in a lake.

Oxygen deficits in the bottom water in summer occur not only in Lake Kortowskie but also in other lakes recultivated with the help of "Olszewski's pipeline." On the tachymictic Lake Rudnickie Wielkie in Grudziądz in 1983-1991 anaerobic conditions were observed mainly in the first days of July and lasted until the end of summer stagnation, i.e. mostly until the end of August [27]. Anaerobic conditions in summer in the bottom water are also very common in Lützelsee. In three summer months extremely anaerobic conditions were observed (<0.1 mg $O_2 \cdot dm^{-3}$) in 33 cases in 1977-1981 and in 51 cases in 1982-1992 [10].

Likewise, the analysis of 17 large lakes (>$2.5 \cdot 10^6$ m^3) recultivated using the hypolimnetic withdrawal method has not revealed distinct shortening of the anaerobic conditions duration in summer [16]. Moreover, no details regarding the operation of "Olszewski's pipeline" had a major impact on aerobic conditions improvement. Hypolimnetic withdrawal, irrespective of duration of the summer stagnation and oxygen depletion period, is a method that largely contributes to an increase of oxygen concentration in the hypolimnion.

Liquidation of the thermal gradient and beginning of autumn turnover, and in consequence improvement of the oxygen conditions in Lake Kortowskie, depend on the amount of water discharged by the pipeline. At the limited withdrawal of the hypolimnion water in 1993 and in 1994 in both parts of the lake, and in 1991 in the southern part, anaerobic conditions were observed yet in September, and in 1993 in the southern part also at the start of October (Fig. 3). In the years of the pipeline's max. operational capacity, oxygen conditions in the same months oscillated around the values of 0.7 to 4.6 mg $O_2 \cdot dm^{-3}$ in the experimental part and 0.3 to 4.2 mg $O_2 \cdot dm^{-3}$ in the reference part [6].

The consequence of the delayed autumn turnover in 1990-1994 was the extension of the anaerobic conditions period near the bottom in the experimental part as compared to the period when the pipeline was operated under max. capacity.

Earlier homothermy and consequently oxygen equilibrium has a positive impact on the oxygen conditions at the end of autumn turnover [25]. The use of "Olszewski's pipeline" in the meromictic Piburger See caused that at the end of the autumn turnover in 1970, six months after the recultivation initiation, the amount of oxygen rose from 40 to 63% saturation [22]. The results obtained by Gächter [8] on Mauensee confirm that along with the years of the pipeline's operation the oxygen deficit at the bottom increased, the range of the anaerobic zone diminished, and the anaerobic conditions during summer stagnation occur with a 1-2-month delay. Nürnberg [16] has indicated that out of 17 analyzed lakes only in 1 case did the duration of anaerobic conditions remain unchanged (Hechtsee in Austria) and in the other it decreased. The same author has also suggested that the range of the anaerobic conditions changes in lakes recultivated using the "Kortowska method" may be dependent on its morphometry. The range and duration of the anaerobic conditions are clearly decreasing in the lakes whose volume is less than $2.5 \cdot 10^6$ m^3.

The vertical range of water deficient in oxygen during the summer stagnation in Lake Kortowskie in the years when the water flow in the pipeline had been limited to 0.05 $m^3 \cdot s^{-1}$ was maximally from 1 m above the bottom in 1992 in both parts of the lake to 10 m under the surface in 1993 and 1994 in the southern part, and to 9 m under the surface in 1993 in the northern part. Deoxygenation of the bottom water in the initial phase of the summer stagnation and subsequently of the substantial water volume was characteristic also in the years when the pipeline operated with the 0.25 $m^3 \cdot s^{-1}$ capacity (max. up to 10 m under the water surface on post S and up to 9 m under the surface on post N) [6]. Irrespective of the water amount discharged by the pipeline, the max. range of the anaerobic conditions was similar. The total volume of water deficient in oxygen in extreme cases in both analyzed periods amounted to 9.6% of the southern part water volume and to 8.8% in the case of the northern part. Before recultivation and in the first years of the experiment the water volume deficient in oxygen equalled, respectively, 42.5% and 35.5% [11].

Unlike in the summer period, when oxygen deficits are observed, winter in lakes where "Olszewski's pipeline" has been used is characteristic of a relatively high oxygen content [19, 22, 23, 25].

The amount of oxygen dissolved in the deeper waters during winter stagnation is determined in part by the duration of ice-cover. In the examined period ice on the lake was present the longest in the winter of 1990/1991, that is 81 days. Despite that, the mean water saturation with oxygen in the layer beneath 7 m in the winter of 1991 reached 78% in the experimental part and 87% in the reference part. At the max. capacity of the pipeline, in the winter of 1985/1986 when ice cover was observed for 105 days, the mean water saturation with oxygen was equal to 55% and 45% (respectively).

Maintenance of good oxygen conditions during winter stagnation in the deep water layers, irrespective of the amounts of the bottom water withdrawn, is a positive effect of the recultivation method practised in Lake Kortowskie.

Conclusions

The above presented results point out that the thermal and oxygen settings in Lake Kortowskie, and in the experimental part in particular, are determined mainly by bottom waters withdrawal to the outflow. Destratification of the water body and the rate of oxygen depletion during summer stagnation occur with various intensity, depending on the amount of water discharged by the pipeline. The outcome of the flow reduction in the pipeline compared to the effects obtained with max. flow, are:

- Little heating-up of the bottom water in the experimental part and thus slower oxygen depletion in the upper hypolimnion at the start of summer stagnation;
- Extension of summer stagnation whose consequence was delayed (by about 1 month) and at lower temperatures autumn homothermy in the experimental part of Lake Kortowskie;
- Increase of water body stability in the southern part of the lake;
- Extension of anaerobic conditions duration at the bottom in the experimental part by about 1 month.

Maintenance of good oxygen conditions during winter stagnation in the deep water is a positive outcome of the applied method, irrespective of the amount of water discharged by the pipeline.

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