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Influence of Limited Water Flow in a Pipeline on the Nutrients Budget in a Lake Restored by Hypolimnetic Withdrawal Method

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Abstract

The study object was Lake Kortowo, restored since 1956 by withdrawing nutrient-rich hypolimnion water directly to the outflow by means of a pipeline. The studies were carried out after limiting the water flow in the pipeline from 0.25 $m^3 \cdot s^{-1}$ to 0.05 $m^3 \cdot s^{-1}$. The nutrients budget analysed in detail for the period of the pipeline operation was later compared to the theoretical budget with a surface outflow only. The maximum reduction of nutrients, and phosphorus in particular, was noted in the second half of summer stagnation when the pipeline was operating. Negative phosphorus accumulation in the summer months was the result of a balanced removal of hypolimnion water through the whole summer stagnation.

Keywords: lake, eutrophication, restoration, hypolimnetic withdrawal, nutrients budget

Introduction

A lake is a dynamic ecosystem, changing over time. Its development usually leads to enrichment and intensification of biological production. This phenomenon is additionally accompanied by morphometric changes of a reservoir as well as physical and chemical alterations of water. The natural process of lake ageing has been intensified in the past decades by fast eutrophication, resulting from increased import of nutrients from allochthonous and autochthonous sources. With this in mind, the necessity to determine sources of nutrients, mainly of nitrogen and phosphorus gains importance, and to estimate the amounts imported to the lake. Besides, detailed qualitative analysis of a lake, equally important is the budget of main nutrients, as the degree of their utilisation as well as output or accumulation in a lake comprise core information about the lake's vulnerability to eutrophication [29]. This also allows preventative actions that would help avoid total lake degradation.

Accelerated eutrophication of reservoirs forces us to seek methods to slow down, halt or reverse the results of this process. The mere cut-down of allochthonous nutrients does not always bring the expected effects [3, 4, 15, 18, 28]. This regards mainly the lakes of a very high trophic status where the main nutrient sources have become bottom sediments. In such cases restoration turns out a necessity, as a set of actions meant to export nutrients from the water ecosystem or to reduce their amount in circulation, by temporary or permanent binding in bottom sediments.

Undoubtedly the basic action to initiate every restoration activity should be cutting off all wastewater inputs [24]. It is of vital importance that not only point sources but also nutrients and organic compounds running off the drainage basin are cut off [16,17]. Implementation of restoration methods is a difficult task, usually long-term and costly, and at the same time risky; therefore, it must be preceded by actions that considerably reduce or eliminate the external sources of pollution.

Currently practised restoration methods can be divided into "restorative" – applied within a reservoir's water bowl, and "protective" methods – concerning its drainage area [5, 9, 10, 11, 17].

Hypolimnion water removal to outflow was first applied as the restoration method in 1956 on Lake Kortowo [19]. Together with hypolimnion water, removed from the lake are settling organic particles and products of their degradation, as well as substances released from the bottom sediments. This results in nutrient impoverishment of water and bottom sediments. The positive results and low costs of the "Kortowo experiment" make it attractive against the background of presently used methods. The costs comprise water gate construction and a pipeline on the lake's bottom. Subsequent restoration runs without any operation expenditures.

Selection of the hypolimnion withdrawal method as an effective method is not optional. The condition for automatic water outflow from the pipeline is a difference in water table in the lake and at the bottom of the pipe's outlet. Decrease of this difference along the course of summer stagnation diminishes the pipeline's efficiency and in extreme conditions - leads to flow die-out. As a consequence, the nutrient-rich near-bottom water does not flow away from the lake and automatically the effectiveness of restoration decreases.

With regard to the lake's water balance and the fact that hypolimnion water should be removed in the peak stage of nutrient release from bottom sediments, and their accumulation near the bottom, special attention should be paid to regulation of water outflow and duration of withdrawal activity.

Material and Methods

Study Object

Lake Kortowskie of 89.7 ha surface area, 5.3 M m^3 volume, 17.2 m max. depth and 5.9 m average depth is located in the Mazurian Lakeland area, and belongs to the group of so-called Olsztyn lakes [25, 27]. The lake bowl is comprised of three morphometrically different sections (Fig. 1): the northern section of max. depth 15.7 m, the southern section of max. depth 17.2 m, and the central section of an even depth of 6 m.

Lake Kortowo is fed by 5 inflows. To the northern part of the lake discharges the 1.6-km long Kortowka River. The river discharges the surface waters from Lake Ukiel. This inflow was polluted with domestic sewage from an emergency overflow on the sewage collector until autumn 1989. On the south-western side of the reservoir discharges Lesny stream, collecting water from the area of 11.3 km^2; 64.5% of this area comprise forests, 18.5% - arable land, and 17 % - pastures and meadows. This inflow receives pollutants from allotments, and since 1993 additionally from a section of a housing estate. 300 m southwards from the stream's inlet a drainage pipeline discharges to the lake, collecting water from a closed valley of about 0.5 km^2 surface area. On the southern side Starodworski stream enters the lake. Its drainage area equals 0.55 km^2. The stream receives pollutants from a section of a housing estate. In the south-eastern part of the lake the Parkowy stream flows in, collecting water from hollows in the nearby area. A very low water flow in the stream and thus negligible nutrient loading carried to the lake with this inflow decide its exclusion from further analysis [22].

From the southern part of the lake the Kortowka River flows out, discharging to the Lyna River. The outflow is also the spot of the pipeline outlet location. The pipeline's parameters are as follows: length - 250 m, diameter – 600 mm, max. flow – 0.25 $m^3 \cdot s^{-1}$ at the upper allowed water level in the lake of 103.2 m above sea level. The pipeline inlet is situated in the deepest hollow in the southern section of the lake (17.2 m). A device set on the outflow allows to close, open and regulate water quantity discharged by the pipeline. Due to the limited water balance in Lake Kortowo, water withdrawal with max. efficiency i.e. 0.25 $m^3 \cdot s^{-1}$ at the beginning of summer stagnation reduces the flow in the pipeline at the end of summer (second half of August and September), and in extreme conditions – causes it to cease. As a consequence, nutrient removal is limited or disturbed and most stay in the lake [21]. In such conditions, an attempt was made to examine the influence on nitrogen

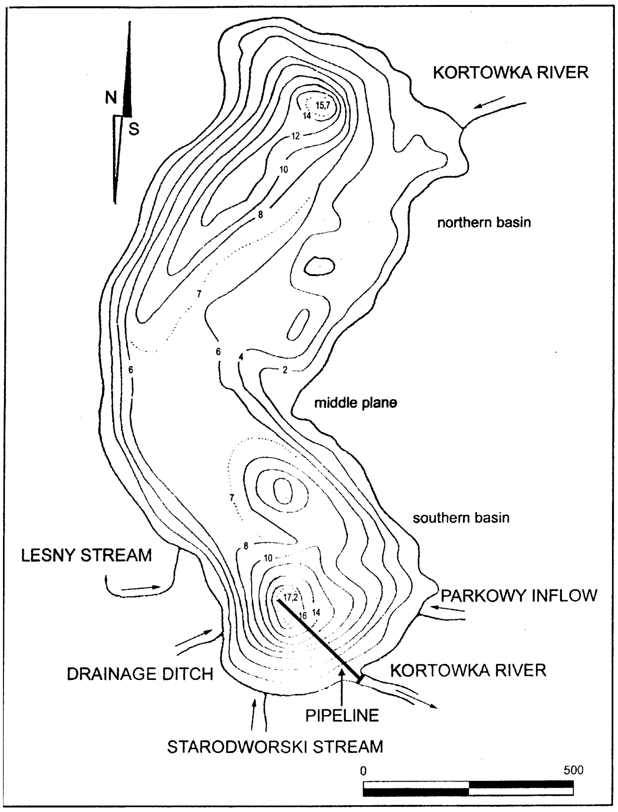

Fig. 1. Bathometric map of Lake Kortowskie.

and phosphorus budget of a limited and thus balanced flow in the pipeline during the whole summer stagnation. For this reason in the period of 1990-1994 in summer and winter months the flow was reduced from 0.25 $m^3 \cdot s^{-1}$ to 0.05 $m^3 \cdot s^{-1}$.

Sampling

The studies of Lake Kortowo at the water flow in the pipeline limited to 0.05 $m^3 \times s^{-1}$ were carried out in the years 1990-1994. Nutrients budget for the individual years has been worked out, with special attention given to the pipeline's operation period, i.e. June through September. The results were analysed statistically.

Nutrients budget (ΔŁ) for Lake Kortowo has been calculated with the use of the Bajkiewicz-Grabowska [1] equation:

$$\Delta \text{Ł} = \text{Ł}_{RK} + \text{Ł}_{PL} + \text{Ł}_{PD} + \text{Ł}_{PS} + \text{Ł}_{ZB} + \text{Ł}_{O} - \text{Ł}_{Odpł.}$$

- Nitrogen and phosphorus loadings imported by the inflows and exported by the pipeline or the surface outflow were calculated based on the results of chemical analyses of the water (all nitrogen and phosphorus forms) and on the flow rates measured at the inflows and the outflow. Next, the daily flow (m^3) was calculated based on the instantaneous flow ($m^3 \cdot s^{-1}$), and multiplied by the determined concentrations of nitrogen and phosphorus compounds thus obtaining the daily loading at the given post. Subsequently, the daily flow and nutrients loading were divided by half of the actual number of days that passed between the two subsequent field measurements. In the calculations the division into calendar months has been taken into account.
- The amount of nitrogen and phosphorus entering the lake from the direct drainage area has been determined with the help of actual runoff coefficients for the individual types of drainage area land.
- Nitrogen and phosphorus input from atmospheric deposition have been determined with the help of unit nutrient input coefficients given by Giercuszkiewicz-Bajtlik [7].

Study results have been subjected to statistical analysis. Relations between quantitative input and output of phosphorus have been determined using the following linear equation:

$$y_1 = a_1 x + b_1$$

$$y_2 = a_2 x + b_2$$

where:
y_1 – phosphorus output by surface outflow,
y_2 – phosphorus output by pipeline,
x – phosphorus input,
a_1, a_2 – constant which can be interpreted as part of phosphorus output,
b_1, b_2 – constant which can be interpreted as part of phosphorus output, irrespective of phosphorus input.

The regression equations have been compared by the method of covariance analysis assuming the significance level of $\alpha = 0.05$. In cases of regression significance in order to compare the averages, the Scheffe's principle of simultaneous tests has been applied.

Results and Discussion

Taking into account nutrients loadings imported to the lake by surface inflows, surface run-off from the drainage area, and atmospheric deposition, the average annual loadings to Lake Kortowo were determined in 1990-1994 of 13,234 kg N and 1,092 kg P. The major part comprised the loadings imported by surface inflows; in the study period it was 62% N and 80% P. Nitrogen and phosphorus annual loadings exported from the lake in the same period equalled 5,809 kg N and 810 kg P. The data given above show that in the examined period 56% of nitrogen input was retained in the lake. In the case of phosphorus it was 26% (Table 1).

Accumulation of 26% calculated in relation to the amount of imported phosphorus points out that the budget for 1990-1994 was favourable in comparison with the budgets for other lakes and dam reservoirs Bajkiewicz-Grabowska et al. [2] report that Lake Wigry retained 48.5% phosphorus. According to Kostecki [12, 13] in Tresna dam reservoir in 1978 accumulation reached 63% Ptot., and in 1979 – 73% Ptot., while in Plawniowice dam reservoir the amount of the retained P-PO_4 in 1976-1993 equalled 53%. The most similar phosphorus budget to that of Lake Kortowo was determined in the years 1984-1991 for Lake Rudnickie Wielkie in Grudziadz (29.9% Ptot.) where also the "Olszewski's experiment" has been applied [20].

Removal of large quantities of phosphorus from Lake Kortowo is related to the pipeline's operation. This can be proved by the nutrient budget calculated for the individual summer months (pipeline operation period). The maximal amounts of nitrogen and phosphorus, in comparison to the inputs by the inflows, were removed from the lake in August. In this month about 2 times more nitrogen and about 3 times more phosphorus were exported from the lake than imported. In September about 27% nitrogen was retained in the lake whereas phosphorus was still withdrawn in large quantities, i.e. 2 times more as compared to the inflow (Table 2).

A very favourable phosphorus budget in years 1990-1994 was observed not only in August and September but also in all summer months, i.e. from June till September.

From the total amount of nutrients imported to the lake in that period retained was 8.9% nitrogen, and phosphorus was exported in the amount of 50.5% exceeding the input value (Table 2). Taking into account that in the discussed period (1990-1994) water quantity feeding the lake was minimal [6] it can be concluded that only the flow in the pipeline limited to 0.05 $m^3 \cdot s^{-1}$ enabled its operation during the whole summer period and thus influenced the amount of exported nutrients.

Negative phosphorus accumulation in Lake Kortowo in the summer months indicates that mainly phosphorus of the bottom sediments origin was removed with the hypolimnion waters. Near-bottom waters removal to the outflow disturbs the balance of concentrations at the sediments–water interface, and increases substances released to the water [19]. Gächter [8] reports that in Mauensee recultivated by the hypolimnetic withdrawal method, the internal loading on the turn of June/July was higher than the external loading by 275 times in 1968, 15 times in 1970, 6 times in 1971, and in August 1974 – 4 times.

Nutrients released from bottom sediments and the subsequent transport to trophogenic layer increases production in a lake [8, 23]. Applying the "Kortowo method" increased transport of nutrients from the sediments to the near bottom waters does not pose a threat to a lake, as they are removed by a pipeline to the outflow. However, the precondition is that the flow in the pipeline is set at

Table 1. Nitrogen and phosphorus budget in Lake Kortowo, 1990-1994.

Budget components	1990		1991		1992		1993		1994		Average 1990-1994	
	N	P	N	P	N	P	N	P	N	P	N	P
	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
Surface inflow	5649	685	4104	478	7471	707	12245	1417	11809	1106	8255	878
Direct drainage area	2467	151	2467	151	2467	151	2467	151	2467	151	2467	151
Atmospheric deposition	2512	63	2512	63	2512	63	2512	63	2512	63	2512	63
Total loading	10627	899	9082	691	12450	920	17223	1630	16788	1320	13234	1092
Outflow by Kortowka River	2769	415	2073	323	3918	493	10653	1588	9631	1230	5809	810
Accumulation	7859	484	7009	368	8532	427	6570	42	7157	89	7425	282

Table 2. Budget of nitrogen and phosphorus in summer months in Lake Kortowo, 1990-1994 (surface inflow minus outflow by pipeline).

Budget components	Month	1990		1991		1992		1993		1994		Average 1990-1994	
		N	P	N	P	N	P	N	P	N	P	N	P
		kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
Surface inflow	June	537	65	355	36	494	71	1424	145	840	127	730	89
	July	265	40	229	22	175	26	1066	124	169	25	381	47
	August	154	22	102	16	88	19	191	45	66	10	120	22
	September	219	28	143	25	396	39	446	71	502	39	341	40
	total	1175	155	829	99	1154	155	3127	385	1577	201	1572	199
Outflow by pipeline	June	176	28	124	9	473	61	2060	253	527	46	672	79
	July	318	63	209	29	351	71	315	65	211	81	281	62
	August	437	87	236	54	94	50	153	65	232	90	230	69
	September	321	58	217	80	121	49	418	171	171	89	249	89
	total	1251	236	785	171	1039	231	2946	553	1141	305	1432	299
Accumulation	June	362	37	231	27	21	10	-636	-107	312	82	58	10
	July	-53	-23	20	-7	-176	-46	751	60	-42	-56	100	-14
	August	-283	-66	-134	-37	-5	-30	38	-20	-166	-81	-110	-47
	September	-102	-29	-74	-55	274	-10	29	-101	331	-50	92	-49
	total	-76	-81	44	-73	115	-76	182	-168	436	-105	140	-101

a level that allows uninterrupted pipeline operation during entire summer stagnation, and especially in the second half when the amounts of nutrients accumulating near the bottom are maximal.

Nutrients budget in Lake Kortowskie at the limited flow in the pipeline in summer months has been compared with a prognosis budget for surface outflow only. It has been calculated that by withdrawing the same water quantity only by the surface outflow, and taking into consideration the concentrations of N and P in the upper water layers (at 1 and 5 m below the water table) the lake would retain 49.6% nitrogen and 57.8% phosphorus i.e. more than when using the pipeline (Table 3).

It should be emphasised that the amount retained in the lake would have actually been even higher than stated above because due to lack of damming devices, especially in spring, excess water would in a short time flow away from the lake and in summer there might have been no outflow.

Removal of higher amounts of nutrients to the outflow with the help of a pipeline in regard to the theoretical surface outflow is undoubtedly the most positive feature of the discussed restoration method, even at a limited hypolimnion withdrawal.

The above statement can be confirmed by statistical analysis, which has resulted in obtaining the following equations:
for phosphorus output by surface outflow

$$y_1 = 0.145 x + 27.098$$

for phosphorus output by the pipeline

$$y_2 = 0.732 x + 57.835$$

Different values of b_1 and b_2 (27.098 and 57.835) indicate that with the pipeline withdrawal more phosphorus is removed, irrespective of the imported amounts. Assuming that the lake receives 100% of phosphorus with the surface inflows, the equations given above would suggest that only the surface outflow exports 14.5% of the directly inflowing phosphorus, whereas in case of the pipeline only the value equals 73.2%. Small accumulation of phosphorus imported to Lake Kortowo during the pipeline's operation results from the fact that the main loading of pollutants enters the lake on the southern side, which is being restored. From the viewpoint of the experiment this is a positive phenomenon as the major part of imported pollutants can be directly withdrawn by the pipeline to the outflow with no accumulation on the bottom sediments.

Having in mind the high vulnerability of Lake Kortowo to eutrophication, resulting mainly from its morphometric parameters, it can be concluded that hypolimnion withdrawal even in limited quantities, is the factor that protects the lake against total degradation. According to the criteria given by Kudelska et al. [14] Lake Kortowo has been classified to the IIIrd category (i.e. lakes with small resistance to degradation) which indicates that even in natural conditions the lake would have not sustain the low trophic condition. Evidence of this was considerable

Table 3. Estimated budget of nitrogen and phosphorus in summer months in Lake Kortowo, 1990-1994 (surface inflow minus surface outflow).

Budget components	Month	1990		1991		1992		1993		1994		Average 1990-1994	
		N	P	N	P	N	P	N	P	N	P	N	P
		kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
Surface inflow	June	537	65	355	36	494	71	1424	145	840	127	730	89
	July	265	40	229	22	175	26	1066	124	169	25	381	47
	August	154	22	102	16	88	19	191	45	66	10	120	22
	September	219	28	143	25	396	39	446	71	502	39	341	40
	total	1175	155	829	99	1154	155	3127	385	1577	201	1572	199
Surface outflow	June	183	13	107	7	295	22	420	33	205	24	242	20
	July	225	19	237	10	261	17	212	26	141	20	215	18
	August	195	23	232	15	73	10	142	17	197	25	168	18
	September	157	21	131	19	94	20	256	43	198	36	167	28
	total	760	77	707	50	723	70	1030	119	740	105	792	84
Accumulation	June	354	52	248	29	199	49	1004	113	635	103	488	69
	July	40	21	-8	12	-86	8	854	99	29	5	166	29
	August	-41	-1	-130	1	15	9	49	28	-131	-15	-48	4
	September	63	7	12	7	302	19	190	27	304	3	174	13
	total	416	78	122	49	431	85	2097	266	837	96	780	115

degradation of the lake yet in the 1950s, prior to "Olszewski's experiment" [26]. Comparison of the high natural vulnerability of the lake to degradation with the high amounts of phosphorus entering the lake from external sources exceeding the permitted loading values by 6.7 times Vollenweider's criterion [30] indicates that the impact of anthropogenic factors is considerable. In such circumstances it is hard to speak about spectacular effects of the restoration by hypolimnetic withdrawal. However, provided the external pollution sources have been cut off, hypolimnetic withdrawal adjusted to the average water balance can optimise the restoration effects in the entire summer stagnation, and especially in its second half. This can be achieved through nutrient impoverishment in the near-bottom waters and in the bottom sediments.

Conclusions

These studies have revealed that replacement of the surface outflow by the hypolimnetic withdrawal, even if limited, allows for removal from Lake Kortowo of high amounts of nutrients (Table 2). Negative accumulation of phosphorus in the summer months of 1990-1994 resulted from the balanced withdrawal of hypolimnion waters between June and September. The flow limited to 0.05 $m^3 \cdot s^{-1}$ right from the start of summer stagnation guaranteed the pipeline's operation also in its terminal phase. Preservation of water flow in the pipeline in the period of peak nutrient accumulation near the bottom is especially important in lakes characteristic of great variations in water balance.

Positive effects of Lake Kortowo restoration by limited hypolimnetic withdrawal confirm that it is justified to install small-diameter pipelines (less efficient) also in deep lakes with vast hypolimnions. It can be very important in cases when the whole restoration activity would have been restricted merely to setting down the pipeline with no constant supervision needed. Where possible, optimisation of the restoration method should be aimed at increasing the amounts of removed nutrients and thus at withdrawing large quantities of hypolimnetic waters in the period of max. concentrations of these elements near the bottom, in proportion to the water balance.

It should be taken into consideration whether replacing the surface outflow by the limited withdrawal of near-bottom waters in the summer period can be used as an additional protective measure in lakes characterized by much difference in nitrogen and phosphorus concentrations between surface and near-bottom layers. Restoration of highly degraded lakes where bottom sediments comprise the main source of nutrient is a long-lasting process, as the nutrient resources in bottom sediments are vast.

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