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How durable is the improvement of environmental conditions in a lake after the termination of restoration treatments

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ABSTRACT

The study was conducted on Lake Długie,a water body lying in Olsztyn, a town situated in northeastern Poland. From 1956 to 1976raw wastewater was discharged into Lake Długie and therefore heavy pollution was the reason for the total degradation of this lake. The concentrations of nutrients were very high in the bottom water layer (TN 22.89 mg L^{-1}, TP 3.50 mg L^{-1}). The mean concentration of chlorophyll an exceeded 60 $\mu g\,L^{-1}$ on average and Secchi disc visibility was less than 1 m. The discontinuation of sewage discharge into the lake caused the saprotrophic state to transform into hypertrophy. Further improvement of the environmental conditions in the lake was possible only after the implementation of an appropriate restoration method. The restoration procedure of this lake began in 1987. The first stage involved an artificial aeration method, and the second stage consisted of a phosphorus inactivation method. The applied restoration methods led to the improvement of Lake Długie's water quality. Even ten years after the restoration treatments ended, TP concentrations did not exceed 0.350 mg L^{-1}, and TN – 3.0 mg L^{-1}. Chlorophyll a contents oscillated in the range of 5–10 $\mu g\,L^{-1}$, and Secchi disc visibility amounted to c.a. 4.5 m.

1. Introduction

Freshwater ecosystems have long been affected by numerous types of human interventions that have had a negative impact on their water quality and ecological state. The acceleration of eutrophication has necessitated the search for effective methods of inhibiting or reversing this process and its adverse consequences. In order to improve the quality of lake water in Poland and around the world, restoration treatments have been developed (Dunst et al., 1974; Gawrońska et al., 2003; Klapper, 1991; Jorgensen, 2001; Klapper, 2003; Cooke et al., 2005; Søndergaard et al., 2007; Dittrich et al., 2011; Dunalska et al., 2015a,b).

One the most often popular lake restoration methods throughout the world is artificial mixing (Grochowska and Gawrońska, 2004; Cooke et al., 2005). The goal is to mix the whole lake water volume, which destroys the stratification in the water body. Thermal and chemical destratification can be obtained, for example by an input of compressed air over the deepest place of the lake. Compressed air is produced by a compressor localized on the shore of the lake. Artificial mixing of water causes radical changes in the chemical stratification in the lake (Cowell et al., 1987).

Another method of lake restoration, firstly implemented in the 1970s, is phosphorus inactivation. This method is basically aimed at reducing the content of bioavailable phosphorus by its precipitation from water and permanent immobilization in bottom sediment (Gawrońska et al., 2007). One of the most popular coagulants is aluminum salts. The advantage of using aluminum salts is that aluminum compounds can create stable complexes with phosphorus, which are insensitive to the redox potential changes (Peterson et al., 1973; Cooke et al., 2005).

Frequently, these methods have had positive effects on lacustrine ecosystems, but results of the manipulations have oftenbeen monitored for just a short period of time after the termination of their application (Kangro et al., 2005; Søndergaard et al., 2008; Özkundakci et al., 2011; Dittrich et al., 2011). There is a great need for longitudinal observational studies of lake restoration effects. For natural water environment, the durability effect should be the most important value. Lake restoration is commonly a very expensive operation, financed by governmental funds, and the proper choice of methods, which can ensure a lasting effect of water quality improvement, seems to be very important.

The aim of the study was to analyse the durability of a change of chosen parameters in the water of an urban lake ten years

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after the termination of the application of two restoration methods: long-term artificial aeration with thermal destratification, and phosphorus inactivation. An alternative hypothesis tested was the presence of significant differences in the mean annual values of nutrients between control year and experimental and post experimental years.

2. Materials and method

2.1. Object of study

The object of the study was postglacial Lake Długie situated on the western part of the town of Olsztyn, situated in northeastern Poland. The lake's surface area is 26.8 ha. The lake has an elongated shape. The lake's bowl divides into three part: a shallow (3 m) and small (2.3 ha) southern bay, the deepest (17.3 m) and largest (13.4 ha) middle section, and the northern section with the maximum depth of 5 m and the surface area of 11.1 ha (Fig. 1, Table 1). The lake bowl volume is 1,415,000 m^3. It has no natural surface outflows and inflows. There is a small peatbog Mszar located nearby, in the direct catchment of the lake, but these two water bodies do not influence each other. In the second half of the last century (1956–1976), this lakereceived raw domestic and storm wastewater (350–400 $m^3 d^{-1}$), which led to the extreme degradation of this body of water and its transformation to a saprotrophic lake type. The inflow of domestic sewage was cut off in 1976 and storm wastewater ceased to be discharged into the lake after year 2000. The discontinuation of sewage discharge into the lake caused the saprotrophic state transform into hypertrophy. Further improvement of the environmental conditions in the lake was possible only after the implementation of an appropriate restoration method.

2.2. Restoration methods description

The first method used for the restoration of Lake Długie was artificial circulation. This procedure was carried out for over ten years, and consisted of two stages:

- during the first stage (in 1987–1990), three ″mini-floc″ type aerators were used, localized in the central, deepest part of the lake (with 150 m intervals), and coupled with a compressor of an approximate capacity of 150 $m^3 h^{-1}$;
- during the second stage (in 1991–1995, 1997, 1998, and 2000), two compressors (working alternately), with the capacity of *ca* 80 $m^3 h^{-1}$, were used together with two ″mini-floc″ aerators, localized in the deepest part and in the northern part of the lake (the distance between them was 360 m).

The failure of the original system to mix completely the water column was the main reason for changing the aeration system elements (such as the compressor type, localization of aerators, and the type of pipes supplying compressed air into aerators) (Grochowska and Gawrońska, 2004). The aeration was conducted to the point where further improvement of water quality in the lake by artificial circulation was no longer possible (due to the excessively low sorptive capacity of bottom sediments – low concentrations of Fe and Mn). It was decided to use another method of restoration, namely – phosphorus inactivation. Subsequently, phosphorus inactivation with a new generation aluminum coagulant called PAX 18 was employed to restore Lake Długie. The treatment was carried out in three stages: in spring 2001, autumn 2002, and autumn 2003. Twenty tons of the coagulant was dosed each time. This corresponded to 6.79 g Al m^{-2} of bottom surface (Gawrońska and Brzozowska, 2002). The coagulant was dosed from barrels on boats and distributed over the entire surface of the lake, through perforated tubes.

Table 1
Basic morphometric data of Długie Lake.

Surface water table	26.8 ha
Maximum depth	17.3 m
Average depth	5.3 m
Relative depth	0.0334
Depth index	0.3
Water volume	1414800 m^3
Maximum length	1670 m
Maximum width	240 m
Elongation	6.9
Average width	160.4 m
Length of shoreline	4080 m
Shoreline development	2.23

	Southern basin	Central part	Northern basin
Surface water	2.3 ha	13.4 ha	11.1 ha
Maximum depth	3 m	17.3 m	5 m
Water volume	42444 m^3	947916 m^3	424440 m^3
Mictic type	polymictic	dimictic	dimictic

Both restoration methods were developed and implemented by the Department of Water Protection Engineering, University of Warmia and Mazury in Olsztyn.

2.3. Research methods

Analysis of the chosen chemical components of water was performed in samples taken using a Ruttner sampler from the central, deepest part of Lake Długie (1 m below the water mirror and 16 m −1 m above the bottom). The water samples for analysis were taken monthly during the period from July to November 1984 (before restoration), and from April to November 1987, 1998, 2000 (artificial aeration), from April to November 2001–2003 (phosphorus inactivation), and from April to November 2011, 2013 (the control year after restoration). The samples were analyzed immediately after their delivery to the laboratory and preservation of samples was unnecessary. Chemical analyses of water were made in accordance with the guidelines given in Standard methods (1999). The water properties selected for analyses were: TN (the sum of TKN determined with the Kjeldahl method, nitrites nitrates), TP (analyzed spectrophotometrically with the molybdenum blue method after preliminary mineralization), chlorophyll a (after filtration using a Whatman GF/C filter and by spectrophotometric method) and water transparency (as Secchi disc visibility). The results were statistically analyzed (one–way ANOVA, $p = 0.05$, Tukey's HSD) using a Statistica 9.0 software package (Statsoft Inc., 2012). An alternative hypothesis tested was the presence of significant differences inmean annual values of nutrients between control year (1984) and experimental years (1987, 1998, 2000–artificial aeration, 2001, 2002, 2003–phosphorus inactivation) and 2011, 2013 (post-experimental years).

3. Results

The statistical analysis revealed significant differences in the content of nutrient in the whole lake's volume (Table 2).

As a result of the two restoration methods, the mean values of TP in surface water layer decreased from 0.279 ± 0.126 mg L^{-1} (in 1984) to 0.054 ± 0.011 mg L^{-1} (in 2003). TP concentrations in the over-bottom water layer decreased thirty times, from 2.911 ± 0.322 mg L^{-1} (in 1984) to 0.098 ± 0.022 mg L^{-1} (in 2003) (Fig. 2). In 2013, there was a slight increase in the TP average value, near the bottom, to 0.175 mg L^{-1} (Fig. 2).