Durability of changes in phosphorus compounds in water of an urban lake after application of two reclamation methods

Jolanta Grochowska, Renata Brzozowska and Michał Łopata

ABSTRACT

The study was conducted on Długie Lake (area 26.8 ha, maximum depth 17.3 m), located in the town of Olsztyn, in north-eastern Poland (the Masurian Lake District). For 20 years starting in the 1950s, Długie Lake was used as a receiver of raw domestic and storm sewage in quantities oscillating between 350 and 400 m$^3$ day$^{-1}$. This led to complete degradation of the lake, known as saprotrophy. After some preliminary protective treatments in the catchment, the lake has been renewed by artificial aeration with thermal destratification and the phosphorus inactivation methods. Long-term reclamation of the reservoir has resulted in distinct and durable improvement of water quality. Before the restoration, the average phosphorus concentration in the surface water layer was 0.079 mg P L$^{-1}$ and in the over-bottom water it reached 2.277 mg P L$^{-1}$. The total phosphorus (TP) level also was very high, i.e. up to 3.5 mg P L$^{-1}$. After the restoration, these values have declined to 0.001–0.017 mg P L$^{-1}$ in the case of mineral P, and the current TP concentrations do not exceed 0.350 mg P L$^{-1}$.

Key words | destratification, lake, phosphorus inactivation, reclamation

INTRODUCTION

Since formation every lake undergoes ageing, known as eutrophication and caused by a constant supply of mineral and organic compounds from the catchment, which accumulate in lakes and are used for autotrophic processes. Under the natural conditions, eutrophication usually progresses very slowly and its rate depends on the lake’s morphology, hydrological conditions and catchment properties (surface shape, geology, soil and vegetation type). Human activity can make a significant contribution to the surface water degradation and accelerate eutrophication. Urban lakes in particular tend to be rapidly destroyed because they are converted to anthropogenic pollution receivers for domestic, industrial and storm wastewater.

Increased pollution of lakes, in addition to unfavorable changes in the physical and chemical water properties, also affects the biological balance (Rast & Thornton 1996; Ellwood et al. 2009; Zhang et al. 2010). Many disadvantageous effects are related to progressive eutrophication, e.g. phytoplankton blooms, deterioration of water transparency, oxygen balance disruption, formation of hydrogen sulfide and internal loading of nitrogen and phosphorus from the sediment.

The rapid acceleration of eutrophication due to human activities has forced researchers to seek effective methods to halt or reverse this process and to alleviate its adverse consequences. In order to improve the quality of lake waters, both in Poland and around the world, reclamation treatments (technical, biological) have been developed, which rely on permanent immobilization of nutrients in lake sediments or on removal of their excess outside a lake ecosystem (Klapper 2003; Cooke et al. 2005). The results of using a particular remediation method, including descriptions of short-term effects, can be found in the world literature (Kangro et al. 2005; Søndergaard et al. 2007, 2008; Dittrich et al. 2011; Özkundakci et al. 2011). However, we lack reports on long-term observations or results of the application of different methods on the same water body.

The aim of this study was to determine the durability of changes in the content of phosphorus compounds in the water of an urban lake (Długie Lake, Poland), which occurred after the application of two restoration methods: long-term artificial aeration with thermal destratification and phosphorus inactivation.
METHODS

The study was conducted on Długie Lake (area of 26.8 ha, maximum depth 17.3 m), located in the town of Olsztyn, in north-eastern Poland (the Masurian Lake District) (Figure 1). The most important morphometric parameters of the lake are presented in Table 1.

Table 1 | Basic morphometric data of Długie Lake

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface water table</td>
<td>26.8 ha</td>
</tr>
<tr>
<td>Maximum depth</td>
<td>17.3 m</td>
</tr>
<tr>
<td>Average depth</td>
<td>5.3 m</td>
</tr>
<tr>
<td>Relative depth</td>
<td>0.0334</td>
</tr>
<tr>
<td>Depth index</td>
<td>0.3</td>
</tr>
<tr>
<td>Water volume</td>
<td>1,414,800 m³</td>
</tr>
<tr>
<td>Maximum length</td>
<td>1,670 m</td>
</tr>
<tr>
<td>Maximum width</td>
<td>240 m</td>
</tr>
<tr>
<td>Elongation/λ</td>
<td>6.9</td>
</tr>
<tr>
<td>Average width</td>
<td>160.4 m</td>
</tr>
<tr>
<td>Maximum effective length</td>
<td>1,225 m</td>
</tr>
<tr>
<td>Maximum effective width</td>
<td>325 m</td>
</tr>
<tr>
<td>Length of shoreline</td>
<td>4,080 m</td>
</tr>
<tr>
<td>Shoreline development</td>
<td>2.23</td>
</tr>
</tbody>
</table>

Długie Lake belongs to the seepage type of lakes, having no natural outflows and inflows. The lake is mainly supplied by direct surface runoff and rainfall.

For 20 years starting in the 1950s, Długie Lake acted as a domestic and storm wastewater receiver (from 350 to 400 m³ per day). During that period, the lake received 1.5-fold more raw sewage than its whole capacity (1,414.8 thousand m³). This led to complete degradation of the reservoir, called saprotrophy. Once the sewage discharge was discontinued, the saprotrophic state changed into hypertrophy. Further improvement of the environmental conditions in the lake was possible only through application of an appropriate rehabilitation method.

The first method used for reclamation of Długie Lake was artificial aeration with thermal destratification. This procedure was carried out for the longest time globally, i.e. more than 10 years. It consisted of two stages:

- the first stage (in 1987, 1988, 1989, 1990) using three ‘miniflocs’-type aerators localized in the central, deepest part of the lake and a compressor with a capacity of approx. 150 m³ h⁻¹;

Another method applied to restore Długie Lake was phosphorus inactivation with a new-generation aluminum coagulant – PAX 18. The treatment was carried out in
three stages: in spring 2001, autumn 2002 and autumn 2003. Each time, 20 tons of the coagulant were dosed from barrels on boats and then dispersed over the lake’s entire surface through perforated tubes.

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

Analysis of the chemical composition of lake water was performed on samples taken in the central, deepest part of Długie Lake (1 m below the water table and 1 m above the bottom). The water samples were taken monthly, from July to November 1984 (before reclamation) and from April to November 1987, 1998 and 2000 (during artificial aeration), then from April to November 2001, 2002 and 2003 (during the phosphorus inactivation treatment), and finally from April to November 2011 (the control year after reclamation). Chemical analyses of water were made in accordance with the guidelines given in Standard Methods (1999).

The results were statistically analyzed (one-way analysis of variance (ANOVA), \( p = 0.05 \), Tukey’s honestly significant difference (HSD)) using a Statistica 9.0 software package (Statsoft Inc. 2010). The alternative tested hypothesis was the presence of significant differences of mean annual values between the control year (1984) and experimental years (1987, 1998, 2000 – artificial aeration, 2001, 2002, 2003 – phosphorus inactivation) and 2011 (post-experimental year).

**RESULTS AND DISCUSSION**

The statistical analysis revealed significant differences in the content of mineral phosphorus (\( P_{\text{min}} \)) in the whole lake volume (Table 2).

Before reclamation, the average concentration of phosphates in the surface water layer was \( 0.079 \pm 0.085 \text{ mg P L}^{-1} \) and \( 2.277 \pm 0.275 \text{ mg P L}^{-1} \) in the over-bottom water layer (Figure 2). During artificial aeration, the mean values decreased to \( 0.04 \pm 0.054 \text{ mg P L}^{-1} \) in the upper water layer and \( 0.080 \pm 0.238 \text{ mg P L}^{-1} \) near the bottom. The P inactivation method caused further reduction in phosphorus amounts to \( 0.001 \pm 0.003 \text{ mg P L}^{-1} \) at the surface and \( 0.017 \pm 0.029 \text{ mg P L}^{-1} \) in over-bottom water (Figure 2). In 2011, the average P concentration increased to between 0.017 and 0.058 mg P L\(^{-1}\) (Figure 2).

The statistical analysis also showed significant differences in the total phosphorus (TP) content (Table 2). As a result of the two reclamation methods, the mean values of total phosphorus in surface water layer decreased from \( 0.279 \pm 0.126 \text{ mg L}^{-1} \) (in 1984) to \( 0.054 \pm 0.011 \text{ mg P L}^{-1} \) (in 2003). Total phosphorus concentrations in the over-bottom water layer decreased 30 times, from \( 2.911 \pm 0.522 \text{ mg P L}^{-1} \) (in 1984) to \( 0.098 \pm 0.022 \text{ mg P L}^{-1} \) (in 2003) (Figure 3). In 2011, there was a slight increase in the total phosphorus average value near the bottom to \( 0.195 \text{ mg P L}^{-1} \) (Figure 3).

In the water of Długie Lake, statistically significant differences in the content of organic phosphorus (\( P_{\text{org}} \)) were found (Table 2). Before the remediation, the organic-form P concentration in the surface water layer was \( 0.199 \pm 0.044 \text{ mg P L}^{-1} \) and near the bottom it was \( 0.633 \pm 0.244 \text{ mg P L}^{-1} \) (Figure 4). In 2011, these values are changed to \( 0.077 \pm 0.082 \text{ mg P L}^{-1} \) in the surface water layer and \( 0.137 \pm 0.078 \text{ mg P L}^{-1} \) in over-bottom water (Figure 4).

The main goal of every reclamation method is to reduce the phosphorus content in water down to a level that can limit primary production. Some of the phosphorus loaded into water is eliminated from the water column due to accumulation in organisms and sedimentation processes. Sediments act as a nutrient trap until their sorption capacity is exhausted. In lakes with an advanced trophic level and oxygen depletion in the near-bottom zone, sediments act as a significant phosphorus source and become the cause of secondary pollution (Selig & Schlungbaum 2003). Substances stored in the sediment may have harmful impacts on lake water quality in the long run.

**Table 2** | Results of one-way ANOVA analyses (with Tukey HSD) for investigated variables in Długie Lake water

<table>
<thead>
<tr>
<th>Variable</th>
<th>( F ) value</th>
<th>( p ) value</th>
<th>Years which differed significantly from 1984 (before recultivation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{min}} ) surface water</td>
<td>9.4654</td>
<td>0.000</td>
<td>2001, 2002, 2003</td>
</tr>
<tr>
<td>( P_{\text{org}} ) surface water</td>
<td>7.7662</td>
<td>0.000</td>
<td>1998, 2001, 2002, 2003</td>
</tr>
<tr>
<td>TP surface water</td>
<td>12.5623</td>
<td>0.000</td>
<td>2001, 2002, 2003</td>
</tr>
</tbody>
</table>

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Prolonged use of Długie Lake as a domestic and storm wastewater receiver led to a high concentration of phosphorus in the lake water (more than 12 mg P L\(^{-1}\)) as well as in the sediment (Brzozowska & Gawrońska 2003). High phosphorus concentrations in the lake water persisted after the sewage flow was stopped in 1984 (Figures 2 and 3), 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 amount can make complexes with iron, another 30% can be incorporated into the phytoplankton biomass, while the remaining phosphorus is dissolved in water. In Długie Lake, the percentage of P bound by the bottom sediments was even lower due to the lack of iron in the water and desorption of complexes with iron, manganese and calcium occurring under the low redox potential conditions (Boers & de Bles 1991). 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 the vertical transport (James et al. 1990).

The enrichment of the surface water layer by the phosphorus originating from the sediment was most noticeable in spring and autumn. The decrease in the mineral phosphorus content during a water circulation period is common in other lakes, but was not observed in Długie Lake, which was due to the anoxic conditions and iron deficit in the lake water, which made it impossible for phosphorus to precipitate as iron(III) compounds. The essential conditions for this process are good water oxygenation and Fe:P ratio above 3 (Søndergaard et al. 2003).

A distinct decrease in the mineral phosphorus amount in the surface water layer was observed in the summer season. In a moderately eutrophic lake, the phosphorus cycle is regulated largely by phytoplankton, and during its maximum development the level of phosphates may decrease to analytical zero. In Długie Lake, despite high primary production (strong oxygen oversaturation in water, high pH, low water transparency, high organic matter content), the total depletion of mineral phosphorus in the water was noted at the end of summer stagnation. It might indicate that a constant loading exists from the drainage basin or from the shallow, epilimnetic sediments rich in phosphorus. Over 40% of Długie 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 (Boström et al. 1982; Forsberg 1989; Shaw & Prepas 1990), nutrients are introduced directly into the

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Figure 2 | \(\bar{P}_{\text{min}} \pm /- \text{ standard of error of the mean (SEM) and standard deviation (SD)}\) in the water of Długie Lake.

Figure 3 | Mean annual values of total phosphorus \((\pm /- \text{ SEM and SD})\) in the water of Długie Lake.

Figure 4 | Mean annual values of organic phosphorus \((\pm /- \text{ SEM and SD})\) in the water of Długie Lake.
trophogenic zone, where they are used by phytoplankton (Stauffer 1987). This study has shown that the use of artificial aeration did not cause significant changes in the total phosphorus content in the surface water layer. But a very large reduction in the phosphorus amount was observed in the over-bottom water. In 1984, before the reclamation, TP concentrations ranged from 2.5 to 3.5 mg P L$^{-1}$. During the first stage of aeration they decreased to ca. 0.5 mg P L$^{-1}$, and from 1998 to 2000 they did not exceed 0.25 mg P L$^{-1}$. The TP decrease in the lake during the aeration was mainly attributed to a decrease in the concentration of mineral phosphorus. In water normally occupied by the hypolimnion, a decrease in phosphates has been reported since the commencement of the reclamation procedure. It was slight in the first year, but in the next few years, especially during the second aeration stage, the phosphate concentration was about 10-fold lower than before the reclamation.

This phenomenon might have been caused by translocation of phosphate into the surface layer and its distribution in the whole water volume. In addition, owing to improved oxygenation of the over-bottom water, release of mineral phosphorus from sediments was inhibited and, consequently, the mineral P concentration decreased in over-bottom water as well as in the whole lake. This assumption is confirmed by the results obtained by Keizer & Sinke (1992), who found that an improvement in the over-bottom water oxygenation can result in decreased diffusive P release in the sediment–water interface.

During the recent years of the artificial aeration treatment, the rate of phosphorus removal from water has decreased. A low content of iron and manganese in the sediments and the absence of these metals in the water column have indicated that further water quality improvement with this method was impossible. Then a decision was made to apply the P inactivation method. This method is based on the precipitation of phosphorus from water and its inactivation in the bottom sediments, whose sorptive properties are improved by an application of a coagulant. Because aluminum forms strong bonds with phosphorus, even under anoxic conditions and a low redox potential, it was decided to apply the aluminum coagulant PAX 18 (polyaluminum chloride, which contains ca. 9% Al) in Długie Lake. The product is widely used in water purification plants in Poland and in Europe in order to improve the quality of potable water.

Prior to inactivation, the phosphate content in the water surface layer was very high (0.02 and 0.06 mg P L$^{-1}$) and increased with the depth, reaching values from 0.11 to 0.60 mg P L$^{-1}$ near the bottom. At the same time, TP ranged from 0.28 mg P L$^{-1}$ at the surface to 0.82 mg P L$^{-1}$ near the bottom, and organic P contributed mostly to the total phosphorus content in the surface water layer.

After the introduction of the first coagulant dose, almost complete precipitation of phosphate from the upper water layer was observed. In the hypolimnion, the decrease in the phosphate amount was low, but the inhibition of the P release from the sediment was evident. After the next PAX 18 doses, no presence of mineral phosphorus was detected in the surface layer, while in the near-bottom zone its concentration did not exceed the value of 0.039 mg P L$^{-1}$. This was the result of a radical blockage of mineral P release from the sediment and was indicated by a decrease in the mineral P amount in the interstitial water (Gawrońska et al. 2002; Brzozowska et al. 2012).

The applied method did not affect directly the content of organic phosphorus. A reduction in the amount of the organic P form was a consequence of depressed production processes due to a drastic reduction in the availability of phosphates for primary producers.

The phosphorus inactivation method helped in reducing the total phosphorus amount in Długie Lake. In 2003, after completing the third stage of this method, the total phosphorus concentrations ranged from 0.054 to 0.144 mg P L$^{-1}$.

The long-term rehabilitation of Długie Lake has changed this saprotrophic lake into a water body on a low trophic level. The current low phosphorus concentration and the observed values of other parameters (chlorophyll $a$ below 4 mg m$^{-3}$, water transparency up to 5 m, biochemical oxygen demand in the range from 1.5 to 3.5 mg O$_2$ L$^{-1}$) confirmed this fact.

In 2011, 7 years after finishing the lake rehabilitation by the phosphorus inactivation method, Długie Lake continued to have good water quality, although a slight increase in the content of mineral phosphorus and TP was observed in the near-bottom zone. It should be noted that the lake lies within the lowest point of the drainage basin and is therefore continuously loaded by natural substances from the catchment. It is possible that in a few years it will be necessary to repeat the phosphorus inactivation procedure in order to further improve the sorption properties of the bottom sediments. This procedure will help to capture the current phosphorus load from the catchment.

**CONCLUSIONS**

The results obtained in this study on Długie Lake show how difficult it is to restore good water quality in a lake degraded by human activity. The applied reclamation methods have
led to the improvement of Długie Lake’s water quality. The research results show that a combination of different reclamation methods applied to the same water body can be good practice. The examined lake is one of the few lakes in the world where restoration has been successful and its effects are seen even after many years.

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