Journal of Elementology ISSN 1644-2296

Grochowska J., Brzozowska R., Parszuto K., Tandyrak R. 2017. *Modifications in the trophic state of an urban lake restored by different methods*. J. Elem., 22(1): 43-53. DOI: 10.5601/jelem.2016.21.2.1058

ORIGINAL PAPER

MODIFICATIONS IN THE TROPHIC STATE OF AN URBAN LAKE RESTORED BY DIFFERENT METHODS*

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Abstract

The rapid acceleration of eutrophication calls for effective methods to reverse or at least decelerate this process and its consequences, such as phytoplankton blooms, deterioration of water transparency, loss of oxygen balance as well as nitrogen and phosphorus internal loading from bottom sediments. Many different restoration methods have already implemented in order to improve the quality of lake water in Poland and around the world. Science reports on lake restoration mostly present short-term results achieved with one method, sometimes with a combination of few technologies, methods. Noteworthy is the scarcity of longitudinal observations and descriptions of persisting changes in environmental conditions and trophic status after a lake restoration process. The aim of the study was to present long-term changes in the trophic status of an urban lake which were been achieved through artificial aeration with thermal destratification and phosphorus inactivation, based on water quality parameters and an analysis of biotic and abiotic conditions prevailing in this lake. The study was conducted on Długie Lake, situated in the town of Olsztyn. This lake had acted as a sink of raw domestic sewage (400 m^3 day^{-1}) for 20 years. After preliminary conservation operations, the lake was restored by the artificial circulation and phosphorus inactivation methods. Prior to the restoration effort, the lake had been classified as hypertrophic, with an average TSI index value of 79. The average chlorophyll *a* concentration was 63 μg l^{-1} and water transparency did not exceed 0.3 m. The implementation of two restoration methods improved the trophic level and the lake became mesotrophic. The improvement seems permanent, as the mean TSI index is 50 ten years since the termination of the restoration procedures.

Keywords: trophic state, TSI indexes, recultivation, hypertrophy, mesotrophy.

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* This study was funded by the Ministry of Science and Higher Education in Poland (problem group No 38 UPB titled “Inland water ecosystems, its protection and restoration of lakes” Subject No 0806.0802 “Improvement of the water reservoirs protection and restoration methods”).

INTRODUCTION

Economic development has resulted in significant degradation and accelerated eutrophication of inland water bodies.

Lakes in urban surroundings, especially, have been exposed to rapid deterioration because of their conversion to sinks of anthropogenic pollution, such as domestic, industrial or storm wastewaters. The rapid acceleration of eutrophication calls for effective methods to reverse or at least decelerate this process and its consequences, such as phytoplankton blooms, deterioration of water transparency, loss of oxygen balance as well as nitrogen and phosphorus internal loading from bottom sediments (STANISZEWSKI, SZOSZKIEWICZ 2010). Many different restoration methods have already implemented in order to improve the quality of lake water in Poland and around the world. Their aim was to improve environmental conditions through permanent immobilization of nutrients in sediments or removal of excess phosphorus and nitrogen beyond a lake (ÖZKUNDAKCI et al 2010, 2011, DUNALSKA et al. 2015*a*,*b*). Science reports on lake restoration mostly present short-term results achieved with one method, sometimes with a combination of few technologies, methods (DITTRICH et al. 2011, JEPPESEN et al 2012, KLEEBERG et al 2012, 2013). Noteworthy is the scarcity of longitudinal observations and descriptions of persisting changes in environmental conditions and trophic status after a lake restoration process.

The main assessment indicators of a lake trophic status are concentrations of nitrogen and phosphorus, oxygen, water transparency and the content of chlorophyll *a*. In addition, indicators of biotic and abiotic components are applied. Among the most popular indicators there is the Carlson Trophic State Index – TSI (CARLSON 1977), which consists of three parameters determining numerical values for the content of chlorophyll *a*, total phosphorus and Secchi disc visibility. Index values are in the range from 0 to 100. The higher the value, the higher the trophic level reached by the assessed water body.

The aim of the study was to present long-term changes in the trophic status of Długie Lake achieved after the implementation of such restoration technologies as artificial aeration with thermal destratification and phosphorus inactivation. The changes were diagnosed according to water quality parameters and an analysis of biotic and abiotic conditions prevailing in this lake.

MATERIAL AND METHODS

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

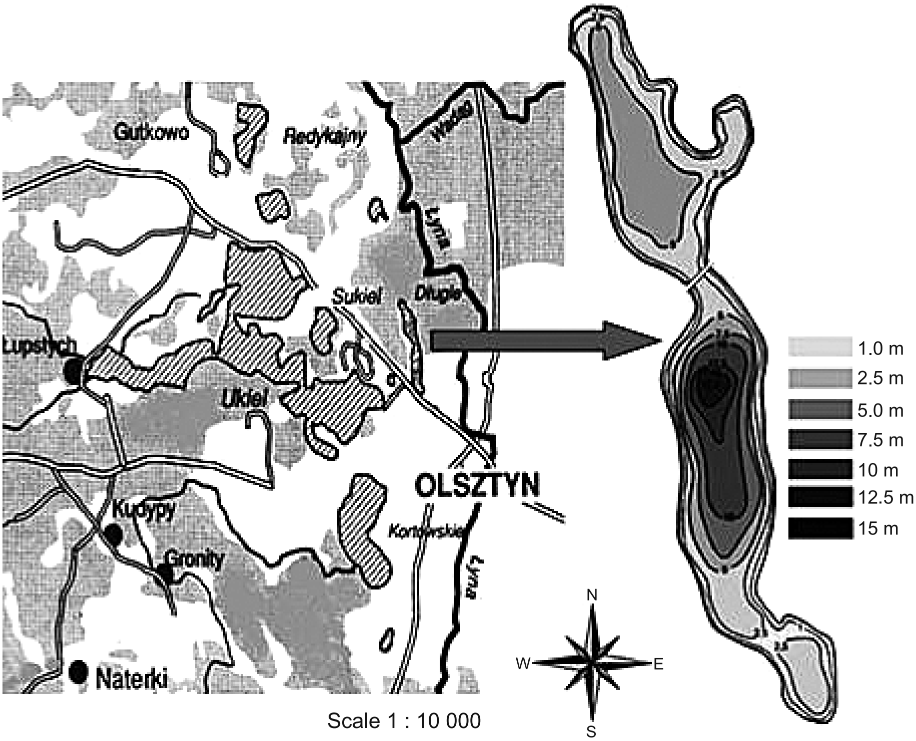

Fig. 1. Research area

Table 1

Basic morphometric data of Długie Lake (Inland Fisheries Institute, 1958)

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	1 414 800 m^3
Maximum length	1670 m
Maximum width	240 m
Elongation	6.9
Average width	160.4 m
Maximum effective length	1225 m
Maximum effective width	325 m
Length of shoreline	4080 m
Shoreline development	2.23

For twenty years since the 1950s, Długie Lake had served as a sink of domestic and storm wastewater (from 350 to 400 m^3 day^{-1}). During this period, the lake received 1.5-fold more raw sewage than its whole volume (1414.8 thousand m^3). This led to a complete degradation of this water body, which became saprotrophic. The influx of domestic sewage was stopped in 1976 and discharge of storm wastewater was discontinued after 2000. This has helped the lake to transform from being saprotrophic to hypertrophic. Further improvement of the environmental conditions in the lake was possible only through appropriate restoration efforts (GROCHOWSKA et al 2013).

The first method applied to restore Długie Lake was artificial circulation. This procedure was carried out for over 10 years, and consisted of two stages:

1) during the first stage (in 1987, 1988, 1989, 1990), three 'miniflox' type aerators were placed in the central, deepest part of the lake and coupled with a compressor of an approximate capacity of 150 m^3h^{-1};
2) during the second stage (in 1991, 1992, 1993, 1994, 1995, 1997, 1998 2000), two compressors (working alternately) of a capacity of *ca* 80 m^3 h^{-1} were used together with two 'miniflox' aerators, placed in the lake's deepest and in the northern parts.

The main reason for changing the aeration system elements (such as the compressor type, localization of aerators and the type of pipes supplying aerators with the compressed air) was the failure of the original system to completely mix the water column (GROCHOWSKA, GAWROŃSKA 2004). Aeration was conducted until further water quality improvement in the lake by artificial circulation was unattainable (due to the insufficient sorptive capacity of bottom sediments, i.e. 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 aluminium coagulant called PAX 18 was used to restore Długie Lake. The treatment was carried out in three stages: in spring 2001, autumn 2002 and in autumn 2003. Twenty tons of the coagulant were dosed each time. This corresponded to 6.79 g Al m^{-2} of bottom surface (GAWROŃSKA , BRZOZOWSKA 2002). The coagulant was dosed from barrels carried in boats and dispersed over the entire surface of the lake through perforated tubes.

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

Analyses of the water chemical composition were performed on samples taken in the central, deepest part of Długie Lake, (1 m below the water table). The water samples for analysis were taken from July to November 1984 (before restoration) and from April to November 2000 (last year of artificial aeration), from April to November 2003 (last year of phosphorus inactivation), from April to August 2013 (the control year after restoration). Chemical analyses of water were made in according to Standard Methods... (1999). Water transparency was measured with Secchi disc (diameter 0.30 m).

The evaluation of the lake's trophic state was based on the OECD trophy differentiation method (Vollenweider, Kerekes 1982) and according to Nürnberg (2001) – Table 2, which relies on the measurements of mean annual

Table 2

Selected criteria for assessing the trophic status of lakes

Trophic state	TP	Chlorophyll *a*		TN
		mean	maximum	
	(µg l-1)	(µg l-1)		(µg l-1)
	OECD (1982)			
Ultra-oligotrophy	≤4	≤1	≤2,5	-
Oligotrophy	≤10	≤2,5	≤8	-
Mesotrophy	≤35	≤8	≤25	-
Eutrophy	≤100	≤25	≤75	-
Hypertrophy	>100	>25	>75	-
	Nürnberg (2001)			
Oligotrophy	≤10	≤3,5	-	≤350
Mesotrophy	≤30	≤9	-	≤650
Eutrophy	≤100	≤25	-	≤1200
Hypertrophy	>100	>25	-	>1200
Trophic indicators TSI (Carlson 1977, Kratzer and Brezonik 1981, Dunalska 2009)				
	$TSI_{TP} = 14.43 \ln(TP)+4,15$ $TSI_{TN} = 54.45+14.43 \ln(TN)$ $TSI_{TOC} = 20.59+15.71 \ln(TOC)$ $TSI_{Chl} = 9.81 \ln(Chl)+30.6$ $TSI_{SD} = 60-14.41 \ln(SD)$			
Oligotrophy	<40			
Mesotrophy	40-50			
Eutrophy	50-70			
Hypertrophy	>70			

and maximum concentrations of TP, TN, and chlorophyll *a*, taken in water under the water table. TSI (*Trophic State Index*) was calculated by the method developed by Carlson (Carlson 1977), Kratzer and Brezonik (1981) and Dunalska (2009). This approach is based on summer concentrations of TP, TN, TOC, Secchi disc water transparency and chlorophyll *a* content, which are transformed into numerical indices, to express the current eutrophication level. The trophic state index (TSI) was determined using the average values of the five properties mentioned above. The equations for computing values of TSI indices and parameters for a trophic state assessment are shown in Table 2.

RESULTS AND DISCUSSION

For twenty years since the 1950s, Długie Lake had served as a sink of domestic and storm wastewater (from 350 to 400 m^3 day^{-1}). This led to a complete degradation of this water body, which became saprotrophic. Beside the extremely high concentrations of total nitrogen (30 mg l^{-1}) and total phosphorus (12 mg l^{-1}) in the lake, there were high amounts of organic matter. BOD_5 values achieved 75 mg O_2 l^{-1}, ChOD reached 42 mg O_2 l^{-1}, and the loss on ignition was 155 mg l^{-1}. Sewage entering the lake had a negative impact on the biological components of the ecosystem. There was a growth of phytoplankton biomass in the waters of Lake Długie, which manifested itself by extremely high values of chlorophyll *a*, such as 200 μg l^{-1} on average and about 500 μg l^{-1} at the highest (Gawrońska et al 2005). The species composition of phytoplankton was poor, with a distinct domination of cyanobacteria and green algae (Grochowska, Brzozowska 2013). A study done after the sewage inflow had stopped showed a distinct change in other water quality variables such as the content of organic compounds and nutrients. The average TSI index value in 1984 was 72, which confirmed the lake's hypertrophy (Table 3). TSI_{TP} (78) reached the highest value, which meant that phosphorus

Table 3

Values of TSI indices in the analyzed research years

Indicator	1984	2000	2003	2013
TSI_{TP}	78	78	64	58
TSI_{TN}	69	62	56	50
TSI_{TOC}	-	59	55	50
TSI_{SD}	70	65	51	50
TSI_{Chl}	70	59	51	44
Mean TSI	72	65	55	50

did not limit primary production. The $TSI_{TP} > TSI_{SD} = TSI_{Chl}$ relationships which were noted at that time revealed that phytoplankton influenced significantly the light dispersion in water, although such factors as N limitation, zooplankton grazing or presence of toxic compounds could limit phytoplankton biomass. According to the OECD criteria (Vollenweider, Kerekes 1982) and Nürnberg (2001), Długie Lake was hypertrophic (TP > 100 μg l^{-1}, chlorophyll *a* > 25 μg l^{-1}) – Tables 2, 4.

Further improvement of the environmental conditions in the lake was only possible after an application of the appropriate restoration method. Through restoration a lake's ecosystem can be depleted of excess nutrients and the lake's productivity can decrease. Many researchers claim (Finger et al. 2013, Siwek et al 2014, Remirez-Herrejon et al. 2015) that the abundance of nutrients (especially in N, P, C) in water is the crucial factor shaping the

Table 4

Values of selected physicochemical indicators in waters of Długie Lake

Indicator	Research year	Range	Mean value	Standard deviation	Number of measure-ments	Research months
TP (mg l^{-1})	1984	0.165 - 0.449	0.28	0.126	6	06-12
	2000	0.152 - 0.264	0.19	0.042	8	04 - 11
	2003	0.031 - 0.069	0.05	0.012	8	04 - 11
	2013	0.041 - 0.082	0.04	0.015	5	04 - 08
TN (mg l^{-1})	1984	2.49 - 3.70	2.91	0.418	6	06 - 12
	2000	0.64 - 2.06	1.49	0.517	8	04 - 11
	2003	0.87 - 1.80	1.23	0.347	8	04 - 11
	2013	0.67 - 0.76	0.74	0.036	5	04 - 08
TOC (mg l^{-1})	1984	-	-	-	-	-
	2000	10.20 - 13.30	12.07	1.050	7	04 - 10
	2003	8.37 - 12.67	10.34	1.277	11	04 - 11
	2013	8.80 - 9.20	9.0	1.042	6	04 - 08
Chlorophyll *a* (µg l^{-1})	1984	57.26 - 67.9	63.45	5.531	3	06 - 08
	2000	8.02 - 46.39	29.39	14.159	6	04 - 09
	2003	5.88 - 13.37	8.77	3.084	6	04 - 09
	2013	3.07 - 9.62	6.34	2.818	5	04 - 08
Visibility (m)	1984	0.30 - 0.30	0.30	0.000	3	06 - 08
	2000	0.60 - 1.10	0.82	0.181	6	04 - 09
	2003	1.80 - 2.80	2.02	0.399	6	04 - 09
	2013	2.40 - 4.50	3.45	0.904	5	04 - 08

amounts of organic compounds amounts produced in a water body. The higher concentration of these elements in water, the higher the trophic status of the water body. This translates into an elevated production of organic matter, which leads to a higher chlorophyll *a* content and low water transparency. A highly significant negative correlation between water transparency and chlorophyll *a* (α = 0.05, n = 18) – Figure 2 was found in waters of Długie Lake. The correlation coefficient value was -0.818, and the equation was SD = -1,132ln(Chl *a*) + 4.86 (Figure 2).

The first restoration method implemented in Długie Lake was artificial aeration with thermal destratification carried out for several years. As a result, the amounts of total nitrogen and total phosphorus decreased tenfold (GROCHOWSKA, GAWROŃSKA 2004). Despite the evident decrease in nitrogen and phosphorus concentrations in Długie Lake, phytoplankton blooms continued to appear, especially in spring and late summer. Although the primary pro-

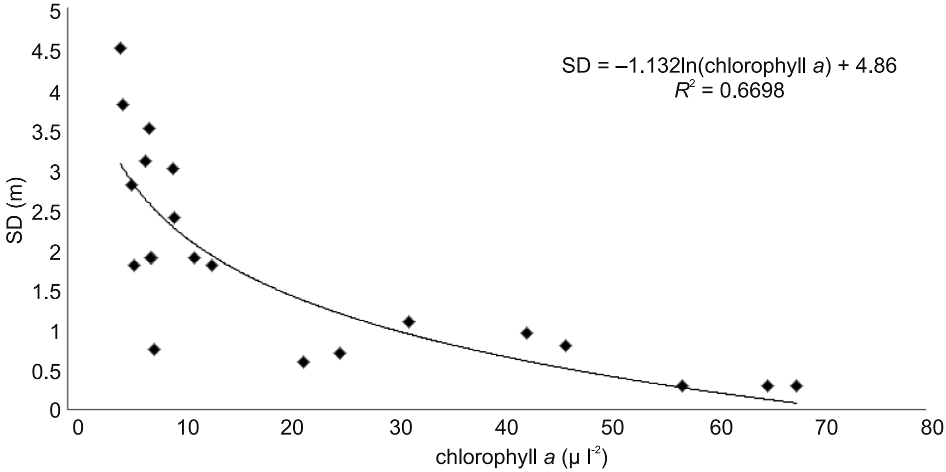

Fig. 2. Correlation between Secchi disc visibility and chlorophyll *a* content

duction indicators were improved, e.g. the mean chlorophyll *a* content was no more than 30 μg l^{-1} and water transparency, which was 0.3 m before the restoration, oscillated around 1 m (Figure 3), the results were less than satisfactory. In the last year of artificial circulation (2000) the mean TSI index

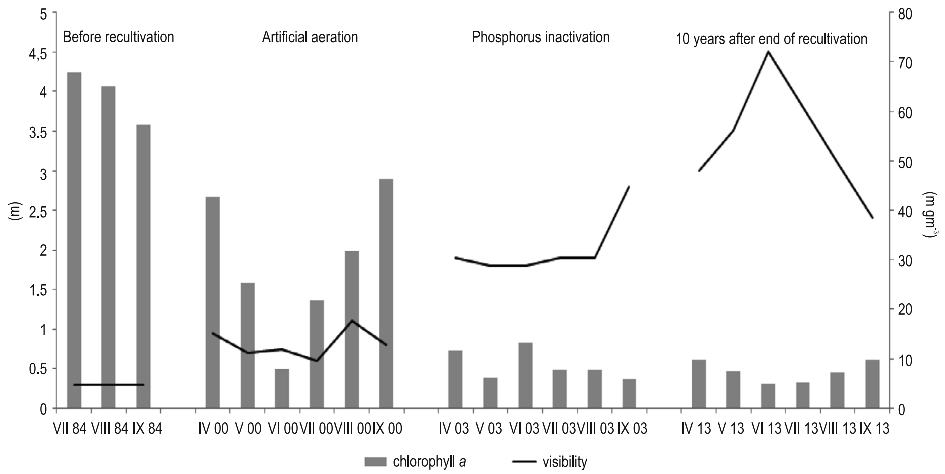

Fig. 3. Changes of chlorophyll *a* content and water transparency in 1984-2013

was 66, hence the lake's trophic status could be classified as eutrophy (Table 2). TSI_{TP} did not change relative to its value before aeration while TSI_{TN} declined from 69 to 62.

A slight decrease was observed in the primary production indexes – TSI_{SD} and TSI_{Chl} (Table 3). TSI_{TOC} (59) remained on the level typical for eutrophic lakes. According to OECD criteria (VOLLENWEIDER, KEREKES 1982) and

Nürnberg (2001) Długie Lake still remained hypertrophic (Tables 2, 4). The low content of iron and manganese in the sediments and the absence of these metals in the water column indicated that possibilities of attaining further water quality improvement by artificial aeration method had been exhausted. Then a decision was made to employ a phosphorus inactivation method. The method is based on the precipitation of phosphorus from water and its immobilization in the bottom sediments. This is achieved by using appropriate coagulants. For Długie Lake, the selected coagulant was PAX 18 (polyaluminum chloride, which contains approxiately 9% Al). Aluminum forms permanent bonds with phosphorus, even in anoxic conditions and at a low redox potential, which justified the choice. The coagulant dosed to the lake water caused precipitation of mineral phosphorus and resulted in a radical decrease of primary production. This effect was evidenced by the observed inhibition of phytoplankton development, a decrease in chlorophyll *a* to 10 μg l^{-1} and an increase in water transparency to almost 2 m (Figure 2). The mean TSI index fell to 55 (Table 3). The TSI_{TP} and TSI_{Chl}, TSI_{SD} were likewise demonstrably lower (Table 3).

Very interesting results were obtained in 2013, which was ten years after the termination of the restoration procedures. Chlorophyll *a* did not exceed 10 μg l^{-1} and the mean water transparency remained at 3.5 m. The values of almost all TSI indices were typical of mesotrophic lakes (Table 3), and the mean TSI index was 50.The chlorophyll *a* and TP values, according to the OECD criteria (Vollenweider, Kerekes 1982) and Nürnberg (2001), were slightly higher than the thresholds for mesotrophic lakes.

These observations reveal the fact that water chemical parameters change very quickly during restoration but biological properties such as chlorophyll *a* concentration and consequent light conditions continue to stabilize for several years after the termination of the restoration procedure. Several years the l restoration treatments, the environmental conditions in the lake were stable and the trophic state of itswaters reached the level of mesotrophy.

The above results demonstrate show how long and difficult it is to restore a badly degraded lake, and what multiple protection and restoration methods must be engaged. The trophic status of Długie Lake was distinctly improved and its productivity drastically decreased through a combination of two methods: artificial aeration and phosphorus inactivation. Today, the analyzed lake is a mesotrophic water body and its aesthetic and recreational values have been regained.

ACKNOWLEDGEMENT

The authors wish to thank Prof. Helena Gawrońska for scientific consultations and Marzena Karpienia, MSc, for making the laboratory analyses.

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