Sustainable Approach to Lake Restoration – An Innovative Treatment Applied in Polish Lakes

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Abstract: A sustainable strategy, involving a combination of physical, chemical and biological methods was proposed as an innovative approach to lake restoration in Poland. We believe that: (i) the interference with the lake shall be limited to the extent that is necessary for the gradual reconstruction of the ecosystem; (ii) attention must be paid to the preservation of biodiversity as an important element affecting the adaptation of the ecosystem in the face of change; and (iii) restoration requires less invasive methods (in comparison with eg. sediment dredging) and nature-based solutions. In the sustainable approach combined methods are used simultaneously, i.e. physical (hypolimnion aeration by means of wind-driven aerator), chemical (phosphorus and ammonium N precipitation with small doses of compounds) and biological methods (supportive stocking with the fry of predatory species). Another innovative method is the direction of spring waters containing high concentration of nitrates to the deoxygenated bottom of the lake. This method increased the redox potential in the sediment-water interface, preventing the release of phosphorus from the bottom to the water column. It should be stressed that all methods are cost effective compared to other methods of restoration, what is of paramount importance for the local administration, being usually sponsors of lake restoration in Poland.

Keywords: lake restoration; nutrients; phytoplankton; sustainability

1. Introduction

Sustainable lake restoration is defined as the simultaneous application of several pro-ecological, non-aggressive methods, preventing the creation of feedback mechanisms in the ecosystem. The inactivation of phosphorus in the water column using small doses of magnesium chloride or iron sulphate (less that 15 kg ha^{-1}) is the key method used in this approach. Chemicals are dosed with the use of mobile pulverizing aerator (so called MAP) in the amount adjusted to the current phosphorus concentration in the lake [1]. The distribution of doses over the vegetation season creates a constant pressure on phytoplankton community, resulting in its gradual reconstruction and, above all, the reduction of cyanobacteria biomass. This *bottom-up* pressure is strengthened by *top-down* impact [2], coming from biological method of restoration – the biomanipulation, leading to changes in fish fauna structure by increasing the quantity of predatory fish. Finally, both methods are supported by water aeration, implemented in this sustainable approach by means of wind-drived aerator for hypolimnetic water aeration [3]. The improvement of oxygen conditions enables the phosphorus binding in the bottom sediment and has a positive effect on the habitat of the organisms inhabiting the lake, including fish and macroinvertebrates.

Another innovative method is the direction of spring waters containing high concentration of nitrates to the deoxygenated bottom of the lake. This method increases the redox potential in the sediment-water interface, preventing the release of phosphorus from the bottom to the water column. Nitrate treatment significantly affects the metabolism of the lake by boosting the activity of

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ubiquitous bacteria at the sediment surface, resulting in the reduction of oxygen uptake by sediments, formation of hydrogen sulphide and increased phosphorus binding [4]. Moreover, nitrates are characterized by higher solubility in water in comparison to oxygen as well as the ability to penetrate into the sediment [5, 6]. We have proposed the utilization of nitrates already present in the lake catchment, coming from fertilizers used on agricultural areas instead of usually used solid chemical e.g. calcium nitrate [6, 7] or nitrate embedded in a matrix of Fe/Al hydroxide [8].

This type of approach is part of the so-called *nature-based solutions*, i.e. solutions aimed at gradual reconstruction of the structure and functioning of the ecosystem without the need to take too deeply intervening actions. Such restoration should be adapted to local conditions, and above all, it should aim at maintaining biodiversity as an important factor influencing the adaptation of the ecosystem to the changes induced in it [9,10]. Additionally, sustainable restoration costs are spread over time, being more acceptable for local authorities, who usually reimburse it in Poland.

2. Combined restoration of deep Durowskie Lake

Lake Durowskie is a dimictic, flow-through, postglacial ribbon-type lake situated in Western Poland (17°12'1"E, 52°49'6"N). The lake surface area is 143 ha, maximum depth 14.6 m, mean depth 4.6 m and volume 11,322,900 m^3 [11]. Progressive eutrophication of Durowskie Lake was observed at the turn of 20th and 21st century, with summer water blooms dominated by cyanobacteria, mainly *Limnothrix redekei* (Goor) Meffert and *Planktothrix agardhii* (Gomont) Anagnostidis & Komárek [12], low transparency (minimally 0.7 m in 2008), oxygen depletion and the presence of hydrogen sulphide in deeper layers of the water column.

A sustainable restoration was begun in 2009 by means of three methods: (i) phosphorus inactivation in the water column using low doses of iron sulphate and magnesium chloride, dosed by mobile pulverizing aerator (ii) hypolimnetic water aeration with the use of two wind-driven aerators, and (iii) biomanipulation, based on pike and pikeperch fry stocking (Fig. 1). The small doses of iron sulphate (4-15 kg ha^{-1}), applied 3-5 times during vegetation season, inactivated orthophosphates in the water column but did not coagulate the suspended solids. Stocking with predatory fish took place at the end of May with 'fingerlings, and it was conducted with variable number of fry [13].

Phosphorus inactivation together with water aeration enhance each other's impact on water quality, resulting in a decrease of orthophosphates and ammonium nitrogen concentrations in the course of 11 years of restoration. The transformations of nitrogen compounds in hypolimnion were determined by variability of oxygen content – when it was low, ammonium N was undergoing nitrification, and then denitrification, leading to the total depletion of nitrates accompanying a reduction of ammonium N. As the oxygen level increased, the role of nitrification was greater as well, and nitrate concentrations were higher. Due to its paramount importance for redox potential positive values in sediment-water interphase, orthophosphates were successfully bounded onto iron compounds, dosing during P inactivation [9].

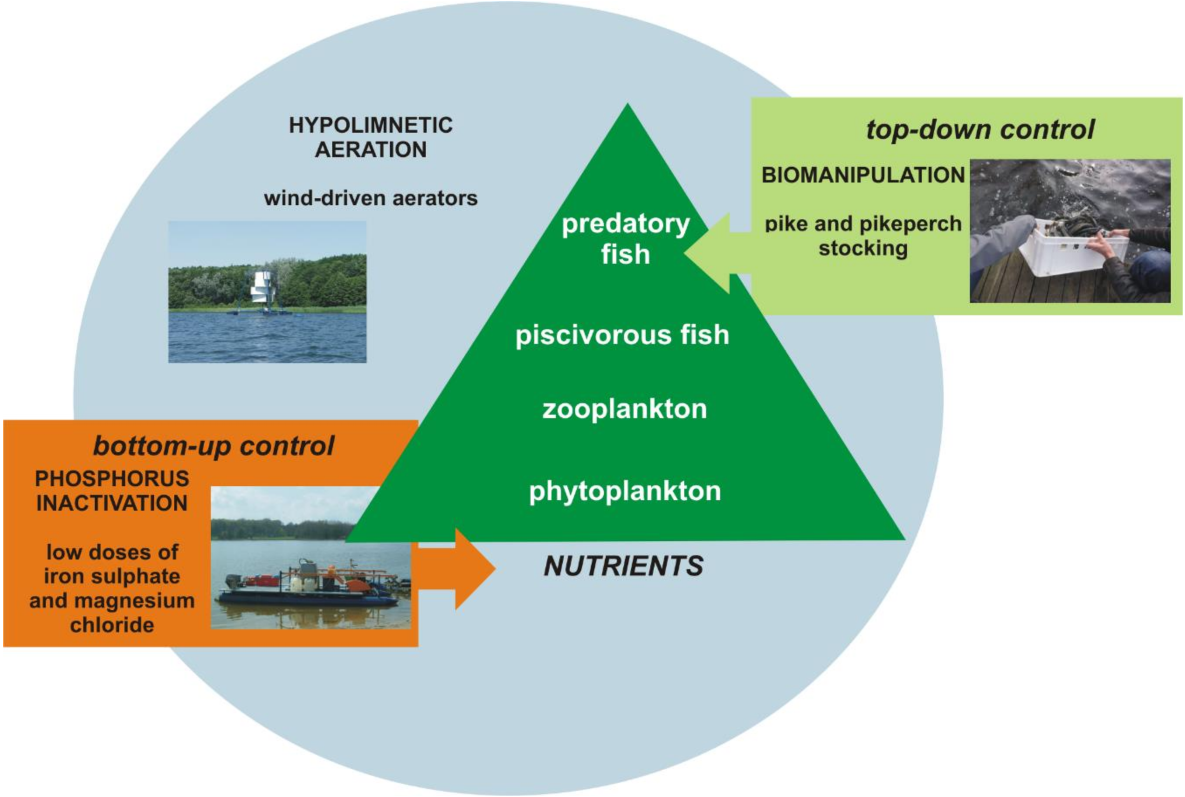

Figure 1. Methods used in the sustainable restoration of Durowskie Lake (photo by: R. Dondajewska-Pielka, K.Kowalczewska-Madura, R. Gołdyn).

This comprehensive approach was supported by biomanipulation, exerting impact on phytoplankton structure, manifested as a reduction of its biomass as well as lower chlorophyll-a content (from *ca* 60 mg m^{-3} prior the restoration to 9-14 mg m^{-3} after 10 years) and higher water transparency (2 m on average). Cyanobacteria were replaced by diatoms, dinoflagellates and chrysophytes, and macrophytes both submerged and nymphaeids (especially *Potamogeton perfoliatus* L.) increased covered area due to higher water transparency [11, 14].

Expected changes were also noted in the matter of internal P loading due to increased accumulation in sediments as well as lower amount of organic matter depositing on its surface and increased oxygen content at the bottom [11, 15].

3. Innovative restoration of Uzarzewskie Lake

Uzarzewskie Lake (52˚27’N, 17˚08’E) is a small, postglacial, kettle-shape lake in Western Poland, with surface area of 10.6 ha, maximum depth 7.3 m and mean depth 3.4 m [16]. It is a hypereutrophic, dimictic and bradymictic lake with a thick layer of bottom sediments, which supplied the lake with a high internal load of nutrients [15, 17, 18]. High phosphorus concentrations in water column resulted in phytoplankton proliferation, manifested in very high chlorophyll-a content (up to 170 mg m^{-3}) as well as low water transparency (0.45 m minimally). Cyanobacteria, including *Cuspidothrix issatschenkoi* (Usachev) P.Rajaniemi, Komárek, R.Willame, P.Hrouzek, K.Kastovská, L.Hoffmann & K.Sivonen, *Dolichospermum spiroides* (Klebhan) Wacklin, L.Hoffmann & Komárek, and *Planktothrix aghardii* dominated in the phytoplankton [19, 20].

Due to intense phosphorus release form sediments, its inactivation with small doses of iron sulphate was started in 2006. Mobile pulverizing aerator dosed the coagulant 6 times in 2006 and 3 times in 2007 in an amount ranging from 60 to 70 kg (380 kg and 180 kg in total, respectively). Although the internal loading has been diminished by 41% [17], water quality improvement was not so clear. Water transparency increased, nevertheless cyanobacterial blooms were still observed, with *Planktothrix agardhii* and *Limnothrix redekei* domination [19, 21].

The main issue was oxygen depletion in hypolimnion, preventing the permanent phosphorus accumulation in sediments on iron hydroxides. Nitrate treatment was selected as a method enabling to create proper conditions for phosphorus binding. This method significantly affects the metabolism of the lake by boosting the activity of ubiquitous bacteria at the sediment surface, resulting in the reduction of oxygen uptake by sediments, formation of hydrogen sulphide and increased phosphorus binding [4]. Moreover, nitrates are characterized by higher solubility in water in comparison to oxygen as well as the ability to penetrate the sediment [5, 6]. We have proposed the utilization of nitrates already present in the lake catchment, coming from fertilizers used on agricultural areas instead of usually used solid chemical e.g. calcium nitrate (Riplox/Limnox method [7]) or nitrate embedded in a matrix of Fe/Al hydroxide (Depox method [8]). In 2008 two watercourses flowing from the springs (9.5^{o}C, 11.5 mgO$_2$ l^{-1} and 36.9 mgN-NO$_3$, on average) were directed towards the hypolimnion (Fig. 2) in order to improve water oxygenation and to raise the redox potential of the bottom sediments.

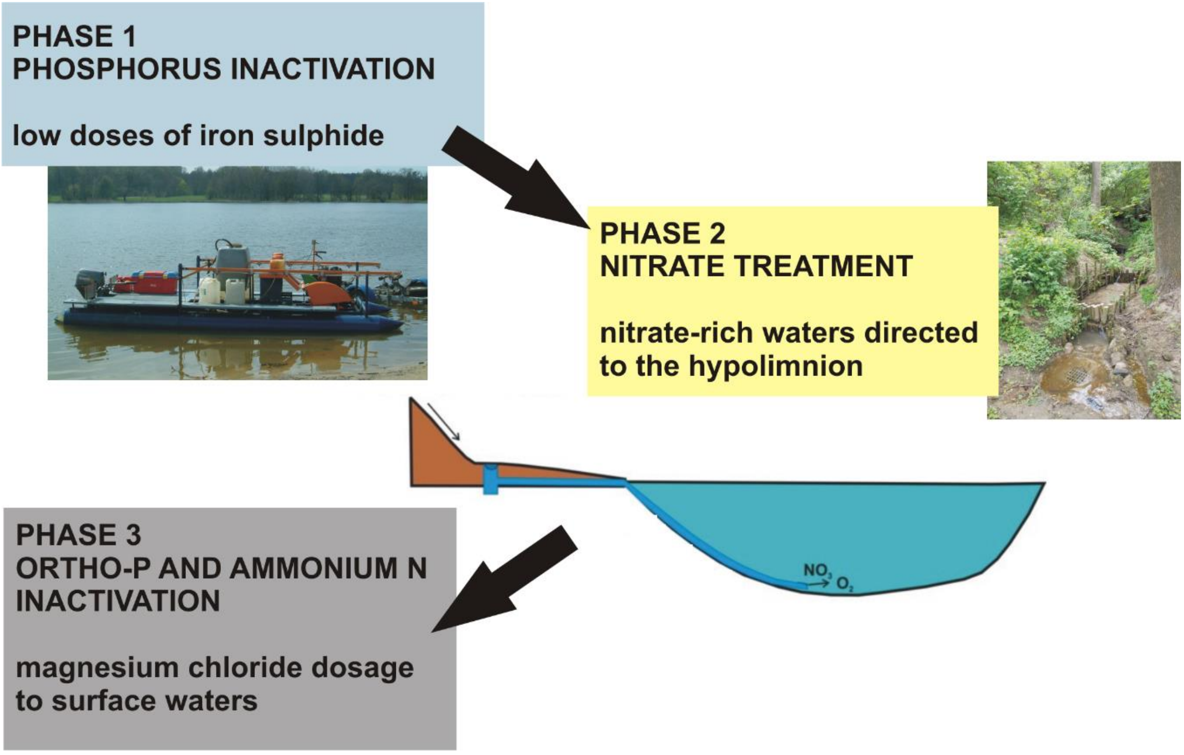

Figure 2. The three phases of Uzarzewskie Lake restoration (photo by: K. Kowalczewska-Madura, R. Dondajewska-Pielka).

As we expected, phosphorus concentrations were significantly reduced in water column [21], mainly due to 10 times lower internal P loading from lake sediments [11, 15]. This phenomenon was possible as denitrification, being the key process of nitrogen compounds transformation in hypolimnion, prevents the reduction of Fe^{3+} to Fe^{2+}. As the nitrate treatment covers the deepest part of the lake, there was a need for additional treatments related to surface waters. Magnesium chloride has been dosed via small inflow in the amount of 25 kg per month since 2017, aiming at the precipitation of both orthophosphates and ammonium N [10]. As a consequence of simultaneous reduction of those mineral forms of nutrients cyanobacteria biomass was diminished [22], especially in case of *Dolichospermum flos-aquae, Planktothrix agardhii* and *Limnothrix redekei.*

4. Conclusions

The sustainable lake restoration, regardless of the specifics of the measures undertaken and the method used, affects both the physical and chemical characteristics of the lake water and the elements of the trophic chain, which interacts with the functioning of the lake ecosystem. Multiannual research revealed that simultaneous application of several methods, which prevents feedback mechanisms, increases the efficiency of restoration. Moreover, this approach is easy to use, energy-efficient and not as expensive as other, more aggressive methods. It is of paramount importance in countries in which the funding for lake restoration is limited, as it is in Poland, and it is usually reimbursed by local authorities.

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