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METHODS APPLIED IN CYANOBACTERIAL BLOOM CONTROL IN SHALLOW LAKES AND RESERVOIRS

METODY STOSOWANE W KONTROLI ZAKWITÓW CYJANOBAKTERII W PŁYTKICH ZBIORNIKACH WODNYCH

Abstract: The eutrophication of freshwaters – including shallow lakes – has become a global problem in the 21st century. Cyanobacterial blooms belong to the most frequent effects of this phenomenon. Although the problem, as well as methods for control it, are known since the beginning of the last century, in the last 25 years we can observe an increasing number of publications concerning methods of bloom control. The paper gives a review of different methods (chemical, physical and biological) applied in cyanobacterial bloom control in shallow lake ecosystems, taking into account not only the effectiveness of the methods but also their impact on other water biocenoses

Keywords: cyanobacteria, algal bloom control, lake restoration, phosphorus inactivation, biomanipulation, barley straw

Introduction

The Water Framework Directive (2000/60/EU) has obliged the Member States of the European Union to improve the quality of theirs water resources, and to achieve a good ecological status of both surface and ground waters by 2015 [1]. This requirement is a difficult challenge for lake managers and local authorities: not only to maintain a good status of water but, in the case of degradation, to also make an effort to restore it.

Overfertilisation is the main factor leading to the degradation of lakes and reservoirs in Europe. The phenomenon is so common that, one could say, the eutrophication of waters has become a global problem [2]. Overfertilisation (phosphorus and nitrogen enrichment) of the water body results in phytoplankton (cyanobacterial) domination (hypereutrophy, a turbid water state) which in turn leads to the ecosystem maltfunctioning, and as a consequence, to the exclusion of the economical and social functions of lakes and reservoirs [3]. Cyanobacterial blooms which have occurred recently in many

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recreational and water supply reservoirs in Poland have brought the owners many problems [4–7].

The risk of eutrophication and the occurrence of cyanobacterial blooms in the lake depends on many factors, such as: the lake basin morphometry, the thermal regime or the dominance of macrophytes [8]. Shallow lakes (which constitute the most common type of lakes in Europe) can show a great resistance to degradation because of the dense macrophyte vegetation which often covers the bottom and which plays a buffering role by maintaining a clear water state [3, 9]. On the other hand, the lack of thermal stratification, which leads to a quick turnover of nutrients during the summer, is one of the disadvantages of the shallow lake ecosystem. But the restoration of shallow lakes is often easier than restoring a deep one, because of the smaller volume of water they have, and because of the positive role of macrophytes which could support the return to a clear water state [10–11].

Cyanobacterial bloom control is a problem that has often been described in scientific papers, particularly in the last 25 years. It could be connected with an increase in restoration programmes in Europe which have been undertaken to fight the blue-green algae or, on the other hand, with the progress of shallow lake ecology, which has greatly expanded our knowledge about the functioning of these ecosystems. A review of the methods for algal bloom control in lakes has been given by, amongst others, Sosnowska [12], Kajak [13] and Klapper [14]. One can also find chapters concerning this problem in books by Cooke et al [15] and McComas [16]. Some of these papers are out of date, while the others are too extensive or focused on one aspect (*eg* technical) of the problem, and do not provide the review of the broad spectrum of methods from hydrological ones to biological ones.

The aim of this paper is to review the various methods applied in cyanobacterial bloom control in shallow lake ecosystems. The analysis was carried out on the basis of several dozen case studies on mainly European lakes in the last 25 years, taking into account not only the effectiveness of the methods but also their impact on other water biocenoses. As a conclusion, a strategy for the effective and environmentally safe control of cyanobacterial blooms is presented.

Reduction of external phosphorus loading

Any measure which is undertaken to eliminate cyanobacterial blooms has a chance of succeeding only in the case of a reduction in the phosphorus external loading into the lake [11, 15]. Lake Washington in the USA remains the model study of this method. In the late sixties the lake was isolated from nutrient rich streams which caused a rapid improvement in the water quality and, consequently, a decline in blue-green blooms several years later [17]. However, a reduction in external phosphorus loading does not always lead to an improvement in the water quality – which was shown by the example of Alderfen Broad in Great Britain (area 7 ha, mean depth 0.8 m). The lake was isolated from several canals which were enriched by nutrients from wastewater treatment plants. Positive changes were noted four years later: water transparency had increased, phytoplankton biomass had declined and macrophytes had covered the bottom. After a short period of recovery, however, the water quality declined again because of strong phosphorus loading from sediments [18]. Jeppesen et al. [19] analysed examples of external loading reduction in thirty five north temperate lakes. In the majority of cases, the water quality of the lakes improved after reduction (a decline in the concentration of TP, TN and chlorophyll *a*, an increase in transparency, a change in the zooplankton structure). But a positive change in the phytoplankton structure and a decline in cyanobacterial dominance was observed only in deep lakes.

A reduction of nutrient external loading into surface waters could be achieved through many measures established in catchments. In Denmark, where most lakes are shallow and rapidly flushed, a lot of programmes for the reduction of nutrients were performed during the last twenty five years. They included such measures as the modernisation of sewage treatment plants, an increased use of phosphate-free detergents, an increased storage capacity for animal manure, regulations on agriculture practices (the establishment of 2 m wide cultivation-free riparian buffer strips along streams; the use of green cover during winter), increased afforestation etc. As a result of these activities a 73 % reduction in the total phosphorus in surface waters has been achieved [9].

Reduction of internal phosphorus loading

The reduction of external phosphorus loading performed as a measure to control cyanobacterial blooms is indispensable, but often insufficient. Blue-greens will also develop if they have an internal source of phosphorus coming from lake sediments. This internal load could be as big as the one delivered from the lake catchment [20]. The phenomenon that phosphorus is supplied mainly from internal sources in overfertilised lakes is more a rule than an exception [15]. Therefore, the process of lake recovery after reducing the external loading of nutrients could be delayed by 10–15 years because of internal loading from sediments [19].

Sediment removal is one of the methods of internal loading reduction. The aim of this measure is to get rid of both phosphorus deposited in the sediments, and of cyanobacterial cells and spores, which could be the inoculum of further blooms [21]. The most simple way to achieve this is by lowering the water level in the reservoir and then removing the dried sediments. Sediments could also be removed by dredging, which is more expensive because of the great amount of wet matter which would have to be stored or utilised [14]. The destruction of bottom fauna during sediment removal is one of the environmental costs of this method. The future restoration of benthos could last up to several years [15]. Sediments have been removed *eg* in lake Cockshoot Broad in Great Britain (mean depth 1 m, area 3.3 ha). After being isolated from the nutrient rich river Bure, the top 70 cm layer of sediments was pumped out. Postive changes were noted immediately after the operation: a decline in the concentration of chlorophyll *a* and phosphorus, an increase in filter feeding cladocerans and the recolonisation of the bottom by macrophytes. Unfortunately, the positive effects only lasted several years. The further strong development of planktivorous fish caused a decrease in the zooplankton population and the return of algal blooms [18]. Similar effects were achieved after the restoration of lake Braband in Denmark (area 150 ha, mean depth 0.8 m), where 500 000 m^3 of nutrient-rich sediments were pumped out. There was no improvement in the water quality because of the dense population of planktivorous fish inside the lake, and the high external nutrient loading [22].

A cheaper technique is sediment capping. In this method a kind of barrier which prevents phosphorus returning to the water column is created. The role of this barrier can be played by sand with an admixture of materials, which can inactivate the phosphorus, such as: zeolits, calcium compounds and clay materials [23–24]. The main problem of this techniqe is the stability of this layer, which can be affected both by the mixing and the activity of benthic organisms [14, 20]. Sediment capping is still tested, mainly in laboratory studies. In the Paldang dam reservoir in Korea (volume 0.9 km^3, max depth 20 m) sediment capping by gypsum was experimentally applied *in situ*. As a result a high reduction (52 %) of chlorophyll *a* concentration was achieved [25].

Phosphorus bonding by sediments could be improved by the oxydation of its upper layer, using a method called RIPLOX. It is achieved by adding some chemicals (*eg* calcium nitrate and ferric chloride) to the sediments, which results in an increase of redox potential. Such conditions support the process of denitrification, which favours phosphorus bonding [26]. This method was applied *eg* in lake Lyng in Denmark (area 10 ha, mean depth 2.4 m). During the two following summer seasons calcium nitrate in doses of 8–10 g N/m^2 were added to the sediments. Preliminary results showed that the method was successful [22, 27]. RIPLOX was also used in the Old Danube lake in Vienna (area 158 ha, mean depth 2.3 m) which is an oxbow lake by the river Danube. Calcium nitrate was applied in doses of 16–240 g N/m^2 which resulted in an improvement in water quality, *eg* a change in the domination in the phytoplankton structure from cyanobacteria to greens and diatoms [28].

Recently, one of the most wide used methods of internal phosphorus reduction is its precipitation and immobilisation. This technique consists of adding of coagulants which form the flocs and, consequently bond the phosphorus and, therefore, makes it unavailable for algae. Additionally, such a suspension caps the sediments and prevents the phosphorus from returning to the water column [15]. The precipitation of phosphorus is the most commonly used method in reservoirs with a slow water exchange rate [14]. The following chemicals are used as coagulants: compounds of aluminium, iron or calcium, as well as clay materials.

Aluminium sulphate was used to reduce cyanobacterial blooms in several cases, *eg* in Green Lake (area 105 ha, mean depth 3.9 m) in Seattle (USA). A substantial improvement of water quality (including an increase in transparency from 1.9 to 6.1 m) had been noted after dosage of 8.6 mg Al/dm^3, but the positive effects lasted only a few years [29]. Similar effects were noted in lake Courtille in France (area 22 ha, mean depth 2.5 m) where 1.5 mg Al/dm^3 was used and in lake Sonderby in Denmark (area 8 ha, mean depth 2.8 m). In both cases, after the water had improved its quality (2 months – 3 years), cyanobacterial blooms returned again [11, 30, 31].

Iron(III) chloride is another coagulant used in phosphorus inactivation. It was applied (mixed with an upper layer of sediments) in lake Groot Vogelenzang in the Netherlands (area 18 ha, mean depth 1.75 m). The decrease of chlorophyll *a*, phosphorus and seston concentration was noted three weeks after the treatment, although because of a high external loading of nutrients the water quality collapsed after several months [32].

Phosphorus can be immobilised through the addition of calcium compounds. Calcium treatment was applied in two north Canadian lakes: Lofty (area 70 ha, mean depth 2.9 m) and North Halfmoon (area 77 ha, mean depth 3.2 m) in doses of 74 and 107 mg $Ca(OH)_2/dm^3$, respectively. As a result, a 16–27 % decrease in internal phosphorus from sediments was noted, but the effectiveness of the treatment was as short as one year. Moreover, there was no decline in the phytoplankton biomass, and a considerable negative effect on the macrophyte biomass was observed [33–34]. Multiple doses of lime were added to two other Canadian lakes: Halfmoon (area 41 ha, mean depth 4.7 m) and Figure Eight (area 37 ha, mean depth 3.0 m) in the amount of 5–78 mg/dm^3. The concentrations of chlorophyll *a* and total phosphorus decreased, as well as the biomass of macrophytes. No negative effects on zooplankton and benthic macroinvertebrates were noted [35].

An example of the clay material which is used in phosphorus inactivation is modified bentonite known as "Phoslock". The use of this preparation was tested *eg* in the river Canning in Australia, where a 1 mm layer of bentonite was created on the bottom sediments of the river. The effects (a very considerable decrease in phosphate concentrations) could be seen immediately after the treatment, but there is a lack of data about the long term results of the treatment [36]. The decrease in phosphate concentrations in the case of two estuaries: Swan-Canning River and Vasse (Australia) was also a result of Phoslock treatment. The triplicate dosage of the preparation created 0.5–1 mm layer on the surface of bottom sediments. Despite phosphate reduction, a decrease in the phytoplankton biomass was observed only in one of these cases [37].

Biological control

It has been argued that a reduction in both external and internal phosphorus sources is the best way for a long term reduction of cyanobacterial blooms in the lake [15]. But the domination of blue-greens in the lake is determined not only by the availability of nutrients, but also by the proper structure of food webs in the ecosystem, *eg* by the appropriate zooplankton phytoplankton ratio. There are a lot of cases where, after a reduction in nutrient loading, cyanobacterial blooms are present, mainly because of a dense stock of planktivorous fish in the lake. The fish suppress the zooplankton population, so the factor which can effectively control the phytoplankton population is lacking [9].

Biomanipulation is the most often used method in the biological control of algal blooms. The method consists of reducing the pressure of planktivorous fish on crustacean plankton which feed on phytoplankton [38]. The desired result can be achieved by stocking the predatory fish or/and by removing the planktivorous fish. As a result the population of planktonic crustaceans increases, generating increased feeding on phytoplankton, which in turn suppresses its population [39]. Benthivirous fish removal is also one of the biomanipulation methods. These fish contribute a lot to the increase in resuspension while feeding in lake sediments, thus increasing the amount of phosphorus in the water column. Therefore, the reduction of the benthivorous fish population can result in a decrease in the phytoplankton biomass in the lake [11]. However, biomanipulation has some disadvantages. One of them is that highly qualified limnologists should be involved. This method is best for smaller reservoirs, because of the requirement to control the entire fish population [15]. Biomanipulation will fail in lakes that are strongly enriched with nutrients – with concentration of total phosphorus greater than 100 μg/dm^3 [9]. In the majority of cases the effects of biomanipulation are not long lasting – after approximately ten years cyanobacterial domination often returns [11].

In Denmark biomanipulation (zooplankton- and bethi-vorous fish removal with additional piscivorous fish stocking) was carried out in a total of forty two lakes. Fish reduction ranged from 10 % to 80 % of the fish stock, which means 100–870 kg/ha of the lake. In many cases positive effects were achieved directly after the measure was taken: in most lakes there was observed an increase in the water transparency, but it was not connected with a decrease in the phosphorus concentration and macrophyte reappearance [11]. An example of a temporarily successful fish reduction is lake Vaeng (area 15 ha, mean depth 1.2 m). Despite prior external nutrient reduction, the biomass of blue-greens remained high. Thus, the removal of 50 % of the population of zooplankton- and benthi-vorous fish was carried out. An increase in water transparency, a decrease in the phytoplankton biomass (including cyanobacteria) and the recolonisation of the bottom by macrophytes was observed as a result of the biomanipulation. As a consequence, these changes resulted in the decrease of nutrient concentrations [9]. Unfortunately, over the following years some negative changes in the fish structure and macrophyte cover have occurred. Thus water quality has returned to the pre-treatment state [11].

In the Netherlands eighteen lakes were biomanipulated in the period from 1987 to 1995. In many cases a significant improvement in water quality was achieved [10] but in the long term perspective (> 10 years), a permanent positive change (the disappearance of cyanophyte blooms) occurred in only two of lakes [11].

Another idea for biological treatment which could be used in cyanobacterial bloom control is the use of phytoplanktivorous fish like silver carp (*Hypophthalmichthys molitrix*) or bighead carp (*H. nobilis*). Besides the fact that both species are alien to waters in *eg* Europe, the method has a lot of disadvantages: fish graze on crustacean plankton and can cause ichthyoeutrophication [40, 41]. Despite this, both species of carps are sometimes used to graze on cyanophyte biomass, especially in Asian countries. Xie i Liu [42], for example, have observed the positive role of high silver carp and bighead carp stock on the decline of cyanobacterial blooms in lake Donghu (area 3200 ha, mean depth 2.2 m) in China.

Aquascaping is a biological method which could support cyanobacterial bloom control [16]. The method involves the re-establishment of macrophytes in the lake, or activities within the lake which can favour this process. Macrophytes interact with phytoplankton *via* several mechanisms, like: the competition for nutrients and light, sediment stabilisation and the limitation of resuspension, the creation of refuges for zooplankton and the secretion of chemicals suppressing algal growth [43].

Hydrological, physical and mechanical methods

Cyanobacterial booms could be also limited by lake flushing or by the dilution of lake water. The aim of these measures is both the reduction of nutrient concentrations and the increase of the water exchange rate, which should lead to intensification of seston sedimentation [15]. The main condition which should be met is that the water used for dilution or flushing should be nutrient-poor. It would generate extra costs if this water had to be purified before use [32]. This technique has been applied since the beginning of 20^{th} century, *eg* in lake Rotsee in Switzerland. The lake was flushed in 1920 by the waters of the river Ruess, but the results were poor, mainly because of the high nutrient content in the water used [15]. There are some examples of lake flushing from the Netherlands, *eg* in the hypereutrophic lake Veluwe (area 3240 ha, mean depth 1.3 m), where nutrient-poor water from polders was used. Phosphorus concentrations decreased and cyanobacterial blooms vanished for one year after the measure was taken but there were no further positive changes, mainly because of the high internal nutrient loading [32].

Cyanobacterial biomass can be also suppressed using ultrasonic radiation [44, 45]. An example of this is lake Senba in Japan (area 32 ha, mean depth 1 m) where a special device was constructed and was operated together with an air pump which, mixed the water column below the system. After two years of the experiment the water quality improved but there is a lack of data about the long term effects of the treatment [45]. Mechanical techniques can also be applied for the same purpose. The mechanical removing of cyanobacterial biomass is a low effect technique, because it is applied mainly to surface algal scums [14, 16]. But Shen et al [46] showed that it could be effective even on a whole lake. In lake Dianchi (area 30900 ha, mean depth 5.4 m) in China, about 400 Mg (tons) of dry cyanobacterial biomass was mechanically removed during a one and a half year period. The process consisted in the shaking, centrifugation, condensation and dehydratation of the biomass. The authors did not provide any data about the long term effects of the technique used.

Chemical methods

The use of many kinds of chemicals, known as algicides, was one of the first methods of algal control [15–16]. Algicide treatment – applied directly to the water body – has a lot of different types of disadvantages: negative effects on other water organisms, short term operation, the release of toxins, and oxygen depletion, which could appear as a consequence of mass cyanobacterial killing [15].

Copper sulphate is the most popular algicide which was formerly used. Because of environmental concerns, this chemical is not widely applied now. Hanson and Stefan [47] analysed the short and long term effects of copper use in cynaobacterial bloom control in five shallow lakes in the vicinity of Fairmont in the USA (the lakes were: George, Sisseton, Budd, Hall, Amber; the area 34–224 ha). The lakes were treated with a dose of 1647 kg $CuSO_4$/ha over a period of more than 50 years. Although the treatment was usually effective in killing cyanobacteria, other effects occurred: an increase in the dead algal biomass lead to oxygen depletion and an increase in the release of phosphorus from the sediments, which consequently resulted in the reoccurence of algal blooms. Very short lasting effects of copper application were also observed in lake Courtille in France (area 22 ha, mean depth 2.5 m), where a dose of 63 $\mu g/dm^3$ Cu^{2+} was applied. The decrease in the chlorophyll *a* concentration and the decline of the blue-green *Microcystis* sp. population were noted directly after the treatment, but the positive effects lasted only two months [48].

Currently, the most popular chemical method in algal control is the use of barley straw. Barley straw is not an algicide itself, but the inhibiting action of this material is connected with its decomposition in lake water, when some algicides (*eg* phenolics, carboxylic acids) are released [49, 50]. The use of this material is cheap, environmentally safe and user-friendly, although it has some disadvantages, such as a lack of influence on some cyanobacterial species [51–53] or even stimulating effects on some bloom-forming species like *Planktothrix aghardii* and *Microcystis aeuruginosa* [54].

Barley straw was applied *eg* in two reservoirs suffering from cyanobacterial dominance: Middle Linacre and Bottom Linacre in Great Britain. While the first one was used as a control, the second one was treated in the spring with 3.5 mln Mg (tons) of barley straw placed in floating bales. After three months positive changes in the phytoplankton structure and its abundance were noted in the treated reservoir [49]. The effect of the long term application of barely straw on phytoplankton was presented by Barett et al [55]. Barley straw was exposed over several seasons in a tap water reservoir in Aberdeen in Great Britain. As a result, 25–50 % decrease in phytoplankton abundance was observed, but unfortunately it was not connected with a decline in cyanobacterial dominance.

Several attempts at limiting cyanobacterial growth are known in which other organic materials were tested. The influence of wheat straw (with negative results) and rice straw (with positive results) was analysed [56, 57], as well as the influence of oak leaves and bark [58], and of mandarin skin and banana peel [59]. However all these reports come from laboratory studies, so the efficiency of these methods applied in a lake or reservoir is unknown.

Conclusions

An extensive analysis of the literature concerning current methods for cyanobacterial bloom control in shallow lakes leads to some conclusions. They are enumerated below and could act as a kind of guide for water managers and local governments having problems with blue-greens in water bodies.

1. A cheap, easy and safe method of cyanobacterial bloom control in shallow lakes is still lacking.

2. Current methods, in the majority of cases, are effective only in the short term (< 10 years).

3. The use of several methods together (but in a specific sequence) appears to be the most effective approach (*eg* isolation from external sources of phosphorus – internal phosphorus inactivation – biomanipulation).

4. A precise analysis of lake or reservoir functioning is needed before undertaking any treatment. The analysis should cover such characteristics of the water body like: the water and nutrient budget, the thermal regime, the structure and chemical composition of sediments as well as the structure of biocenoses and food webs. Good diagnosis will help to choose the best and most suitable method.

5. The permanent withdrawal of cyanoabcterial blooms in any shallow lake without a reduction in external and internal sources of phosphorus is impossible.

6. Although the application of algicides is effective, it is short lasting. Barley straw exposition is the cheapest and the most user-friendly method, but its real effectiveness is still unknown.

7. The knowledge about the effects of most methods on water biocenosis is still poor, therefore any given method should be tested in the laboratory or in enclosures before being applied to the whole lake.

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METODY STOSOWANE W KONTROLI ZAKWITÓW CYJANOBAKTERII W PŁYTKICH ZBIORNIKACH WODNYCH

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Abstrakt: Jednym z globalnych problemów XXI w. jest eutrofizacja wód śródlądowych, w tym płytkich jezior, której częstym efektem są zakwity cyjanobakterii planktonowych. Problem zakwitów sinic znany jest co najmniej od początku poprzedniego stulecia, podobnie jak i sposoby walki z tym negatywnym zjawiskiem, jednak to w ciągu ostatnich 25 lat, wraz z rozwojem ekologii płytkich jezior, daje się zauważyć wzrost liczby publikacji na temat nowych metod kontroli zakwitów. W artykule przedstawiono przegląd różnorodnych (chemicznych, fizycznych i biologicznych), aktualnie stosowanych metod ograniczania nadmiernego rozwoju cyjanobakterii w płytkich zbiornikach wodnych uwzględniając zarówno ich skuteczność, jak i wpływ na inne biocenozy wodne.

Słowa kluczowe: sinice, zakwity wód, rekultywacja zbiorników wodnych, inaktywacja fosforu, biomanipulacja, słoma jęczmienna