Artificial mixing to reduce growth of the blue-green alga *Microcystis* in Lake Nieuwe Meer, Amsterdam: an evaluation of 7 years of experience

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Abstract The problem of Lake Nieuwe Meer (area = 1.3 km^2, max. depth 30 m, P_{tot} = 500 mg/m^3) was extensive growth of *Microcystis* with disturbing scum forming. Since 1993 the lake has been artificially mixed in summer by a bubble plume installation. The result is quite successful since the mass of *Microcystis* is up to 20 times lower than in the years before mixing and no scum is present any more. The study in Lake Nieuwe Meer showed a shift from cyanobacterial dominance (mainly *Microcystis*) to flagellates, green-algae and diatoms when artificial mixing was applied. Total phosphorus and nitrogen concentrations did not change as a result of mixing and had apparently no effect on the shift in the phytoplankton composition. The chlorophyll-a concentration was much lower in the mixed lake as a result of dilution. The total algae biomass decreased. The transparency did not improve. The total heat energy of the lake is slightly higher than before mixing but still remains in the range of annual fluctuation. The temperature on the surface is approximately 2°C lower. In the whole water-body oxygen was always higher than 5 mg/l. Living space for fish is therefore wider.

The installation in Lake Nieuwe Meer consists of flexible pipes near the sediment, built in a way to prevent sediment erosion and transport into the water. There are no constructions in the water-body. All mechanical parts are on land. The layout of the installation is shown in Fig. 1. Installed compressor energy is 85 kW. This is equivalent to an upper middle-class motor-car. The design was made specifically for this problem. It is based on the physical data of the algae and the plant.

It would be beneficial to use this 7 years' experience for further applications e.g. elimination of toxic algae in drinking-water reservoirs.

Keywords Artificial mixing; bubble plumes; cyanobacteria; dams; lake restoration; *Microcystis*; Nieuwe Meer; removal; reservoirs; toxins

Introduction

Eutrophication (enrichment with nutrients) of fresh water systems is often accompanied by cyanobacterial dominance. The cyanobacterium *Microcystis* can cause considerable problems in lakes and reservoirs due to bloom-forming and possible production of toxins and off-flavours. *Microcystis* is often abundant in deep lakes, which have high stability in summer with temperature stratification. *Microcystis* benefits from a stable water column in which it exploits the advantage of buoyancy (provided by gas vacuoles) to stay in the euphotic zone and suffers hardly any sedimentation losses. Other non-buoyant algae, like green algae and diatoms, have high sedimentation losses in a stable water column and lose the competition with *Microcystis* in this situation.

When the cyanobacteria release toxins, they can cause health problems for swimmers and death of cattle (Codd *et al.*, 1989). Numerous intoxications of humans are documented (Carmichael *et al.*, 1985 and the National River Authority Report, 1990). The few existing results (Keijola *et al.*, 1988) suggest that elimination in treatment plants may be quite unsatisfactory unless activated charcoal is employed.

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A shift from cyanobacterial dominance to a phytoplankton community dominated by green algae and diatoms has been observed in artificially mixed lakes and reservoirs and several explanations have been offered for this shift (see references).

Lake Nieuwe Meer is used as a regional recreation area. The problem was extensive growth of *Microcystis*. In summer a big green carpet of algae covered the water-surface and oxygen was depleted in the hypolimnion. Since 1993 the lake has been artificially mixed in summer by a bubble plume installation. The result is quite successful since the average mass of *Microcystis* is up to 20 times lower than the years before mixing and no scum is present any more.

In this article we give a description of the aeration installation and we present results of 7 years of mixing in Lake Nieuwe Meer. Further applications are discussed at the end.

Artificial mixing

Artificial mixing in Lake Nieuwe Meer is achieved by a bubble plume installation. Pressurised air is conducted to the lake bottom. The water from the lower layers reaches the surface, is spread out and flows back to the ground. *Microcystis* is prevented from staying in the euphotic zone and is thus hindered in its growth.

The main morphometric lake data are: area = 1.32 km^2, volume = 17.98 Mio. m^3, length = 2.65 km, max. depth = 30 m, mean depth = 18 m, water residence time = 16 to 32 years.

The installation in Lake Nieuwe Meer consists of flexible pipes near the sediment, built in a way to prevent sediment erosion and transport into the water. There are no constructions in the water-body. All mechanical parts are on land. The layout of the installation is shown in Fig. 1. Installed compressor energy is 55 kW + 30 kW = 85 kW. This is equivalent to an upper middle-class motor-car. Energy cost can be reduced by intermittent running of the plant. This is mainly applied in the Spring season. During the sinking period of the *Microcystis* (late afternoon and early night) the installation may also be turned off (Jungo et al., 1995, 1994).

The design was made specifically for this problem. It is based on the physical data of the algae and the plant. Special attention has to be taken of the fact that *Microcystis* is using gas vacuoles to enhance its floating capacity and that it also forms colonies. This means that the velocity of the vertical movement varies at a very high rate, e.g. 1:20 for Lake Nieuwe Meer. Detailed calculations were made with the help of computer-simulations developed for that problem. The design is a process of successive approaches with different layouts of the plant to reach an optimum. Biological knowledge of *Microcystis*, lake data and monitoring were provided from the University of Amsterdam (L.R. Mur, PM. Visser) and Water Authority Rijnland, (J. Stroom). Design and calculations for the plant were made by Jungo Engineering Ltd., Zurich.

Results and discussion

In Table 1, the maximum and average rising velocities of *Microcystis* colonies determined in Lake Nieuwe Meer and Lake Zegerplas are shown. The rising velocities of the colonies in Lake Nieuwe Meer were higher than of the colonies in Lake Zegerplas. For comparison, the velocities of *Anabaena* colonies and *Planktothrix* filaments are also given. These were much lower than *Microcystis* colonies of Lake Nieuwe Meer.

In Fig. 2, the composition of the phytoplankton in percentages (averages in August) is shown during two years without mixing and 5 years with mixing. The percentage of cyanobacteria was about 80% when the lake was stratified (in 1990 and 1991). During mixing of the lake in the later years, the percentage of cyanobacteria varied between less than 5% and 25%. Flagellates, green algae and diatoms were all abundant in the phytoplankton. Within the cyanobacteria, *Microcystis* was dominant in 1990 and 1991, but in the years

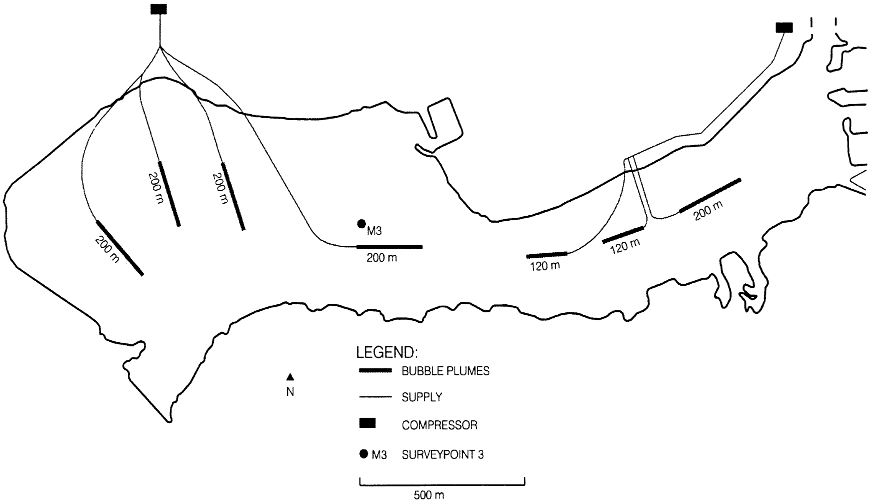

Figure 1 Lake map with bubble plumes.

Table 1 The rising velocities of the cyanobacteria *Microcystis, Anabaena* and *Planktothrix* in the lakes Nieuwe Meer, Zegerplas and the Haarlemmermeerse Bosplas.
* Mean maximum, absolute maximum approx. 250 cm h^{-1}

Lake	Maximum [cm h^{-1}]	Average [cm h-1]
Nieuwe Meer (*Microcystis*)	143*	11.2
Zegerplas (*Microcystis*)	42.1	2.7
Bosplas (*Anabaena*)	4.5	1.2
Bosplas (*Planktothrix*)	4.1	0.8

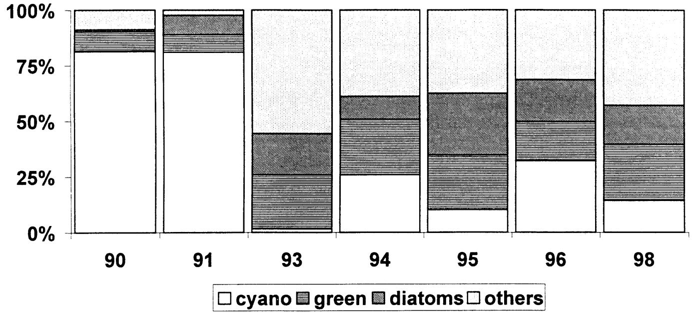

Figure 2 The percentage of the different algal groups (cyanobacteria, green-algae, diatoms and others) in Lake Nieuwe Meer in the years without (90 and 91) and with (93-99) artificial mixing.

when mixing was applied, *Microcystis* was not dominant anymore, *Aphanizomenon* and *Anabaena* were present also. No problem from scum occurred in the years when the lake was mixed.

In Table 2, the physical and chemical variables of the lake are shown. The total contents of both nitrogen and phosphate were not changed when the lake was mixed. Higher concentrations of dissolved P and N and less organic P and N were found in the mixed lake. The chlorophyll-a concentration had also decreased, but the transparency remained almost the same with or without mixing. The total algae biomass decreased (Stroom, 1999).

Table 2 The summer averages (April-September) of total nitrogen (N), total phosphorus (P), chlorophyll-a and transparency in Lake Nieuwe Meer without (before 1993) and with (after 1993) artificial mixing.

year	tot-N [g m^{-3}]	Tot-P [g m^{-3}]	Chl-a [mg m^{-3}]	Transparency [m]
1987	3.8	0.44	63	1.7
1988	3.8	0.47	17	1.9
1989	3.7	0.43	46	1.7
1990	3.1	0.34	38	1.4
1991	–	0.44	–	1.8
1992	–	–	–	–
1993	4.0	0.43	13	1.4
1994	4.0	0.41	6	1.8
1995	4.1	0.37	8	1.7
1996	5.2	0.60	14	1.1
1997	4.2	0.53	3	3.2
1998	3.6	0.36	6	2.1
1999	3.2	0.31	8	2.0

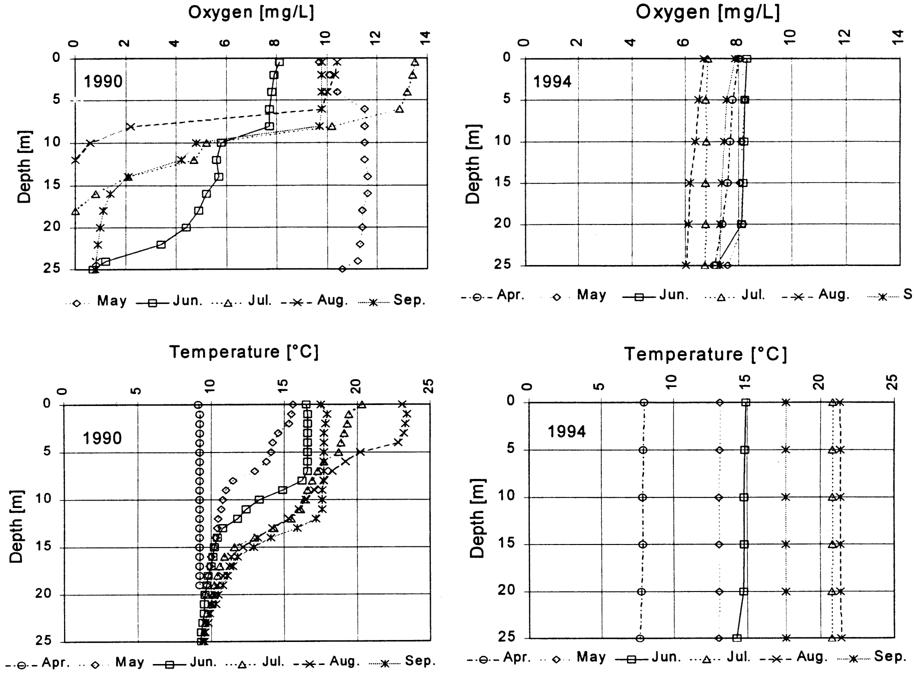

Figure 3 Oxygen and temperature situation before and with mixing.

The study in Lake Nieuwe Meer showed a shift from cyanobacterial dominance to flagellates, green algae and diatoms when artificial mixing was applied. This evaluation of over 7 years of mixing clearly shows that mixing decreased the cyanobacterial dominance. The deep mixing was apparently very unfavourable for the cyanobacteria, in contrast to the green algae and diatoms, which were more abundant due to decreased sedimentation losses in the mixed lake.

As appears from Table 2, total phosphorus and nitrogen concentrations did not change as a result of mixing and had apparently no effect on the shift in the phytoplankton composition. The dissolved nutrient concentrations were so high, and in the mixed lake even higher, that light limitation of the phytoplankton was evident. The higher dissolved nutrient concentrations were probably due to a lower concentration of algae in the water. The chlorophyll-a concentration was much lower in the mixed lake as a result of dilution, but the transparency did not improve.

Two major growth determining factors must be addressed: irradiation and nutrient supply. Artificial mixing will be most successful in reducing the biomass of light-limited phytoplankton populations, because mixing will make this limitation more stringent due to a lower light availability. If the phytoplankton is nutrient-limited, the biomass can increase by deeper mixing due to a higher nutrient availability.

A distinction must be made between colony-forming and filamentous cyanobacteria when prevention of cyanobacteria by artificial mixing is discussed. Colonies have a much higher flotation velocity and the mixing velocity of the water needs to be high enough to keep the colonies entrained in the turbulent flow. Filamentous or single-cell cyanobacteria have a much lower flotation velocity (see the velocities of *Planktothrix* in Table 1), which makes the mixing speed of the water of less importance. Furthermore, from experiments in enclosures (Reynolds *et al.*, 1984) it appeared that the response of two cyanobacteria were very different: *Microcystis* was hampered in its growth by deep mixing while *Oscillatoria* was favoured by deep mixing. This suggests that artificial mixing to control *Microcystis* will only be effective in lakes with rather deep areas (the mean depth of Lake Nieuwe Meer is 18 m). In The Netherlands, *Oscillatoria*-dominated lakes are mostly shallow (< 4 m, Schreurs, 1992), and are usually wind-mixed. It can be expected that artificial mixing will not reduce the *Oscillatoria* biomass in these lakes. In a rather shallow lake with a mean depth of 6 m and a maximum depth of 11 m, artificial mixing was successful in reducing *Oscillatoria* biomass at the beginning (Steinberg and Zimmermann, 1988), but only when intermittent mixing (in a daily or weekly rhythm) was applied.

Visser *et al.* (1996a) showed a simple method to test the efficiency of the mixing. Determination of *Microcystis* in the mixed Lake Nieuwe Meer showed that on sunny, calm days, colonies could escape the mixing in some locations that were apparently less completely mixed. In these less mixed locations, accumulation of *Microcystis* in the upper layer occurred.

An optimal installation is always a compromise between effect and cost. The efficacy of the mixing is therefore not the same in all parts of the lake, i.e. without maximum effort there are small areas with less mixing capacity. For the overall result this is insignificant.

In cases where mixing was not successful in reducing cyanobacteria (Knoppert *et al.*, 1970; Lackey, 1973; Osgood and Stiegler, 1990, Visser *et al.*, 1996b), this might have been due to insufficiency of the plant and/or not enough rather deep areas in the lake or reservoir.

The total heat energy of the lake is slightly higher than before mixing but still remains in the range of annual fluctuation. The temperature on the surface is approximately 2°C lower. In the whole water-body oxygen is always higher than 5 mg/l. Living space for fish is therefore wider.

Conclusions

The problem of Lake Nieuwe Meer was extensive growth of *Microcystis* with disturbing scum forming. Since 1993 the lake is artificially mixed in summer by a bubble plume installation. The result is quite successful since the mass of *Microcystis* is up to 20 times lower than in the years before mixing and no scum is present any more. The study in Lake Nieuwe Meer showed a shift from cyanobacterial dominance (mainly *Microcystis*) to flagellates, green-algae and diatoms when artificial mixing was applied.

Bubble plumes are a sensible solution to reduce algae growth. They are particularly useful as a rapid remedy in case of high over-fertilisation as is the situation in Lake Nieuwe Meer. To be successful the plant must be designed specifically for the problem. It has to be flexible to follow the variations of nature. Other problems influenced by (for example) oxygen and temperature, have to be taken into consideration. The present level of knowledge and practical experience make it possible to design and dimension such installations.

Reservoir management may be split into external and internal measures. External measures tend to reduce the input of harmful substances. Looking back on the last 20 years, we realise that in most cases the goals have not been achieved and often the loads are higher than before (Jungo, 1997). Progress of measures in the drainage area is primarily dictated by economic realities and only secondarily by political or ecological intentions. These intentions are necessary and mark the beginning of a better ecological understanding, which makes us hope that the measures to limit overloading will progress.

At least on a medium time-scale basis, we have to deal also with internal measures like bubble plumes. They are an efficient, low-cost and low energy method to reduce algae growth, to improve reservoirs and attain suitable conditions for drinking water-supply. Consequently, processing of drinking-water can be reduced to a lower level of both technology and cost. Toxic cyanobacteria in reservoirs can be eliminated to prevent health problems.

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