Water Research 97 (2016) 69–82

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Geo-engineering experiments in two urban ponds to control eutrophication

Guido Waajen [a, b, *], Frank van Oosterhout [a], Grant Douglas [c], Miquel Lürling [b, d]

[a] Water Authority Brabantse Delta, P.O. Box 5520, 4801 DZ Breda, The Netherlands
[b] Aquatic Ecology & Water Quality Management Group, Department of Environmental Sciences, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[c] CSIRO, Land and Water, Centre for Environment and Life Sciences, Private Bag 5, Wembley, WA 6913, Australia
[d] Department of Aquatic Ecology, Netherlands Institute of Ecology (NIOO-KNAW), P.O. Box 50, 6700 AB Wageningen, The Netherlands

A R T I C L E I N F O

Article history:
Received 28 April 2015
Received in revised form
25 November 2015
Accepted 30 November 2015
Available online 15 December 2015

Keywords:
Lake restoration
Dredging
Lanthanum-modified bentonite
Phoslock®
Polyaluminiumchloride
Biomanipulation

A B S T R A C T

Many urban ponds experience detrimental algal blooms as the result of eutrophication. During a two year field experiment, the efficacy of five in situ treatments to mitigate eutrophication effects in urban ponds was studied. The treatments targeted the sediment phosphorus release and were intended to switch the ponds from a turbid phytoplankton-dominated state to a clear-water state with a low phytoplankton biomass. Two eutrophic urban ponds were each divided into six compartments (300–400 m^2; 210–700 m^3). In each pond the following treatments were tested: dredging in combination with biomanipulation (involving fish biomass control and the introduction of macrophytes) with and without the addition of the flocculant polyaluminiumchloride, interception and reduction of sediment phosphorus release with lanthanum-modified bentonite (Phoslock®) in combination with biomanipulation with and without polyaluminiumchloride; biomanipulation alone; and a control. Trial results support the hypothesis that the combination of biomanipulation and measures targeting the sediment phosphorus release can be effective in reducing the phytoplankton biomass and establishing and maintaining a clear-water state, provided the external phosphorus loading is limited. During the experimental period dredging combined with biomanipulation showed mean chlorophyll-*a* concentrations of 5.3 and 6.2 $\mu g\ L^{-1}$, compared to 268.9 and 52.4 $\mu g\ L^{-1}$ in the control compartments. Lanthanum-modified bentonite can be an effective alternative to dredging and in combination with biomanipulation it showed mean chlorophyll-*a* concentrations of 5.9 and 7.6 $\mu g\ L^{-1}$. Biomanipulation alone did not establish a clear-water state or only during a limited period. As the two experimental sites differed in their reaction to the treatments, it is important to choose the most promising treatment depending on site specific characteristics. In recovering the water quality status of urban ponds, continuing attention is required to the concurrent reduction of external phosphorus loading and to maintaining an appropriate fish community.

1. Introduction

Most of the world's lakes are small and generally in the size class 0.1–1 ha (Downing et al., 2006). In urban areas such small lakes or ponds are important components of the living environment. Through their ornamental function and recreational opportunities, they enhance the quality of urban life. Urban ponds provide the most important public contact with surface waters (Birch and McCaskie, 1999) and the need for safe and aesthetically acceptable water is critical in modern societies (Steffensen, 2008). Urban ponds also play a role in water retention and as a recipient of sewer overflows. Many urban ponds suffer from eutrophication with severe impacts on water quality and on the aquatic ecosystem (Brönmark and Hansson, 2002; Grimm et al., 2008). Eutrophication and the consequential growth of excessive, sometime toxic phytoplankton biomass is a major water quality issue (Smith and Schindler, 2009).

* Corresponding author. Water Authority Brabantse Delta, P.O. Box 5520, 4801 DZ Breda, The Netherlands.
E-mail addresses: g.waajen@brabantsedelta.nl (G. Waajen), jean.vanoosterhout@wur.nl (F. van Oosterhout), Grant.Douglas@csiro.au (G. Douglas), miquel.lurling@wur.nl (M. Lürling).

http://dx.doi.org/10.1016/j.watres.2015.11.070

In many eutrophic fresh waters, the submerged macrophytes disappear with a transition to a turbid, phytoplankton-dominated state (Scheffer et al., 1993) often with a predominance of cyanobacteria (Watson et al., 1997; Smith et al., 1999). Cyanobacterial blooms can cause fish kills, are potentially toxic to humans, dogs, water fowl and other animals, reduce biodiversity, and can cause unpleasant surface scums and malodors (Codd et al., 2005; Smith et al., 1999; Smith and Schindler, 2009). Cyanobacterial nuisance is a widespread phenomenon in eutrophic urban ponds in The Netherlands (Waajen et al., 2014) and many other countries (e.g. Fastner et al., 1999; Rahman and Jewel, 2008; Willame et al., 2005).

To mitigate eutrophication and hence blooms of cyanobacteria, external phosphorus (P) sources need to be reduced and, depending on the P loading history of the water body and the societal acceptable time for recovery, also the internal P source needs to be addressed (Gulati and van Donk, 2002; Søndergaard et al., 2007; Schindler et al., 2008). Eutrophication mitigation should aim to reduce the P loading below a critical threshold in order to realize a clear water state (Janse et al., 2008) and mitigate cyanobacterial nuisance. Ideally, water managers could select from a number of effective treatments to mitigate cyanobacterial nuisance in urban ponds, improve the water quality and promote the growth of submerged macrophytes, based on a thorough system analysis. However, in many systems repeated maintenance measures are needed, including deliberate manipulation of in–lake/pond processes to enhance recovery, also known as geo-engineering (Spears et al., 2013; MacKay et al., 2014).

Removal of sediment can be an effective in–lake/pond measure in eutrophication control (Peterson, 1982; Brouwer et al., 2002) and is often conducted, but the costs in Dutch urban ponds are high and vary between € 25 and € 60 per m^3 of in situ sediment, including transport and treatment costs. An attractive alternative to sediment dredging which might reduce the costs, is the in situ capping of sediments with an active barrier capable of capturing nutrients released from the pore water and minimizing their release to the water column (Drábková, 2007; Gibbs et al., 2011; Hart et al., 2003). A promising active capping agent is the lanthanum-modified bentonite clay (LMB) Phoslock® developed by CSIRO Australia (Douglas, 2002). Lanthanum is effective over a wide pH range in binding P (Douglas et al., 2004) and shows a very high P removal over the pH range 5–9 (Peterson et al., 1976; Ross et al., 2008). Importantly, the P-binding capacity of lanthanum is not affected by anoxia (Copetti et al., 2016; Douglas et al., 2004; Gibbs et al., 2011; Ross et al., 2008). These characteristics make LMB a promising agent in reducing the sediment P release, although humic substances can reduce its efficacy (Dithmer et al., 2016; Douglas et al., 2000; Lürling et al., 2014). Several studies have shown that the LMB is highly efficient at both stripping soluble reactive phosphorus (SRP) from the water column and in intercepting P released from the sediments once settled where it forms a reactive capping (Akhurst et al., 2004; Douglas et al., 2008; Egemose et al., 2010; Gibbs et al., 2011; Robb et al., 2003; Ross et al., 2008; Van Oosterhout and Lürling, 2013). LMB has also been applied successfully in combination with a low dose flocculant polyaluminiumchloride (PAC) or iron chloride to two stratifying lakes in The Netherlands shifting them from a eutrophic state, dominated by cyanobacteria, to an oligo-mesotrophic clear water system (Lürling and Van Oosterhout, 2013; Waajen et al., 2015). Little, however, is known about the effectiveness of the LMB in shallow eutrophic urban ponds in comparison with sediment removal.

To compare the effectiveness of dredging to that of chemical P inactivation by the LMB (with and without PAC as flocculant), we conducted a compartment experiment in two hypereutrophic urban ponds during 2009–2011. Both ponds had a history of P loading. Excessive fish stocks (often dominated by carp: *Cyprinus carpio carpio*; Waajen et al., 2014) are known to keep urban ponds turbid via sediment resuspension, hence preventing submerged macrophyte establishment (Cline et al., 1994; Meijer et al., 1999; Persson and Svensson, 2006; Roozen et al., 2007; Zambrano and Hinojosa, 1999). As both ponds studied were excessively stocked with carp, both sediment dredging and sediment capping were deemed ineffective without a reduction of fish stocks. Hence, the compartments were standardized with respect to their fish stock and biomanipulation, which involved a reduction in fish stock plus introduction of macrophytes. This was also tested as an individual treatment. We hypothesized that the combination of biomanipulation and measures targeting the internal P load would be effective to create and maintain a clear water state without high phytoplankton biomass.

2. Material and methods

2.1. Study sites

Pond Dongen is located in the urban area of the city Dongen (The Netherlands, N 51° 37′ 48.00″/E 4° 56′ 27.30″) and has an area of 2500 m^2. The water depth is approximately 0.7 m and the pond has a ~0.7 m accumulated soft sediment layer on a sandy base. Until 2000 the pond received the discharge from a mixed sewer overflow. The pond has a history of cyanobacterial blooms (*Microcystis* sp., *Planktothrix* sp., *Anabaena* sp.) and scum formation. Prior to the research, submerged macrophytes were absent in the pond. The initial fish biomass was 1212 kg fish ha^{-1} (Table 1) as was determined on 9 April 2009 by combined seine netting (mesh size 8–12 mm) and electro fishing (5 kW; Kalkman, 2009b). The pond is used for angling and consists of two sections connected by culverts. In August 2009, the pond was divided into eight rectangular compartments by wooden sheet pilings (Fig. 1). Each compartment had a surface area of approximately 300 m^2 and six compartments were used in this study (ranging 210–420 m^3). The pond is not connected to other surface water sources and is hydrostatically maintained by groundwater infiltration (Supplementary information, Appendix A). In dry periods, however, the water level is maintained through the supply of pumped groundwater. During very wet periods, excess water can be discharged through the sewer, but this did not happen during the experiment. During the experiment the external P loading of the compartments was reduced as angling and use of bait were prohibited and the feeding of water birds with associated fecal input was discouraged.

Pond Eindhoven is located in the north of the city Eindhoven (The Netherlands, N 51°48′96.57″/E 5°47′65.31″) and has an area of ~7000 m^2. The average water depth is 1.5 m and the pond has a ~0.4 m accumulated soft sediment layer on a sandy base. The pond

Table 1
Initial fish stock of pond Dongen and pond Eindhoven (kg fresh weight ha^{-1}). Percentages are given in parentheses.

Fish species	Pond Dongen		Pond Eindhoven	
	Fish stock (kg ha^{-1})	(%)	Fish stock (kg ha^{-1})	(%)
Carp (*Cyprinus carpio carpio*)	1010.5	(83%)	450.6	(49%)
Roach (*Rutilus rutilus*)	162.2	(13%)	94.6	(10%)
Bream (*Abramis brama*)	20.3	(2%)	81.7	(9%)
Gibel carp (*Carassius gibelio*)	14.8	(1%)	265.4	(29%)
Rudd (*Scardinius erythrophthalmus*)	2.6	(<1%)	1.7	(<1%)
White bream (*Blicca bjoerkna*)	1.6	(<1%)		
Pike (*Esox lucius*)			20.9	(2%)
Tench (*Tinca tinca*)			8.5	(1%)
Perch (*Perca fluviatilis*)			3.7	(<1%)