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Management of eutrophication in Lake De Kuil (The Netherlands) using combined flocculant – Lanthanum modified bentonite treatment

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ABSTRACT

Eutrophication of Lake De Kuil (The Netherlands, 6.7 ha, maximum depth 9 m) has frequently caused cyanobacterial blooms resulting in swimming bans or the issue of water quality warnings during summer. The eutrophication was mainly driven by sediment phosphorus (P)-release. The external P-loading was in the range of the critical loading for phytoplankton blooms. Hence, the reduction of the internal P-loading provided a promising way to reduce cyanobacterial blooms. To mitigate the cyanobacterial blooms, the combination of a low dose flocculant (iron(III)chloride; Flock) and a solid phase phosphate fixative (lanthanum modified bentonite; Lock) was applied in May 2009. This combined approach both removed cyanobacterial biomass from the water column and also intercepted P released from the bottom sediments. Immediately after treatment, the Secchi depth increased from 1.5 m up to 5 m. Sediment P-release decreased from 5.2 mg P m^{-2} d^{-1} (2009) to 0.4 mg P m^{-2} d^{-1} (2010) but increased in later years. Mean summer concentrations of total P decreased from 0.05 mg L^{-1} (1992–2008) to 0.02 mg L^{-1} (2009–2014) and chlorophyll-*a* from 16 µg L^{-1} (1992–2008) to 6 µg L^{-1} (2009–2014). Mean summer Secchi depth increased from 2.31 m (1992–2008) to 3.12 m (2009–2014). The coverage of macrophytes tripled from 2009 to 2011. In the winter of 2010/2011 *Planktothrix rubescens* bloomed, but cyanobacterial biomass decreased during the summers after the Flock and Lock treatment in comparison to prior years. After the Flock & Lock the bathing water requirements have been fulfilled for six consecutive summers. As the sediment P-release has gradually increased in recent years, there is a risk of a reversion from the present mesotrophic state to a eutrophic state.

1. Introduction

In The Netherlands around 100 million tonnes of sand, gravel and clay is excavated from the Dutch subsurface annually, most of which is used immediately in construction (TNO, 2015). These excavations are not only located around the main river branches, but also in the sandy southern province North Brabant where at least 146 sand excavations are known. Such excavations fill with water and the resultant new lakes (≥6 m water depth, ~10 ha mean area) are intensely used by citizens to whom they provide amenities including angling, boating, recreation and swimming. The implementation of the European Water Framework Directive (WFD; Council of the European Union, 2000) and the European Bathing Water Directive (BWD; Council of the European Union, 2006) has resulted in considerable attention to the maintenance of acceptable water quality. However, over decades many of the once oligotrophic waters have become turbid, phytoplankton dominated systems (Smith et al., 1999). The phytoplankton blooms, which are often cyanobacteria-dominated, are due to the fertilization with nutrients derived from local surface and groundwater inputs. A range of management interventions including flushing, mixing, the

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application of algaecides and biomanipulation are being used to mitigate the negative effects of eutrophication. Long term restoration, however, can only be achieved if the total nutrient loading is sufficiently reduced (Søndergaard et al., 2007). Although several nutrients are relevant for phytoplankton growth, the emphasis in lake recovery is on phosphorus (P) reduction (Carpenter, 2008; Jeppesen et al., 2007; Schindler et al., 2008), indicating still the present day validity of Golterman (1975) who stated: "*It is not important whether phosphate is currently the limiting factor or not*, *or even that it has ever been so*; *it is the only essential element that can easily be made to limit algal growth*." Phosphorus reduction implies the reduction of the external and the internal P-loading (Gulati and Van Donk, 2002; Søndergaard et al., 2007). In lakes created by excavations, the internal P-loading may often be the main driver for sustaining phytoplankton growth (Burger et al., 2007) and delays recovery for a substantial period after the reduction of the external P-loading (Jeppesen et al., 2005). Removal of sediments enriched in P is a common method to reduce the internal P-loading (Peterson, 1982), but it is not always effective (Geurts et al., 2010) and is expensive (Welch and Cooke, 2005) in terms of recovery, but also for dewatering and long term disposal. This explains the need for alternative methods to control the sediment P-release (released as phosphate) and internal P-recycling in lakes. As a consequence, the interest in P-sorbing materials is growing (Hickey and Gibbs, 2009; Spears et al., 2013b).

A promising novel method has been applied in the former sand excavation site, Lake Rauwbraken (The Netherlands) that has experienced intensifying cyanobacterial blooms since 2000 onwards, before this official bathing site underwent restoration (Lürling and Van Oosterhout, 2013). A system analysis of the lake revealed that internal P-loading was about ten times higher than external P-input. In light of the high proportion of diffuse inputs, mostly through groundwater, a combined phytoplankton flocculation/precipitation and sediment capping treatment was developed. In short, the cyanobacteria biomass was effectively removed from the water column using a low dose polyaluminiumchloride (PAC at <1 mg Al L^{-1}) as flocculant with increased density provided by two tonnes of a lanthanum (La) modified bentonite (LMB). Thereafter, the settled matter and sediment were covered with an active barrier of the LMB designed to capture P released from decaying settled matter, sediment and incoming groundwater (Lürling and Van Oosterhout, 2013). The LMB was developed by CSIRO Australia (Douglas, 2002) and has a strong binding capacity for P (Meis et al., 2012; Spears et al., 2013b) with the capacity to remove P from the water column during settling, and once settled being able to intercept P released from the sediments (Robb et al., 2003; Akhurst et al., 2004; Ross et al., 2008; Egemose et al., 2010; Gibbs et al., 2011; Van Oosterhout and Lürling, 2013). The P-binding capacity of the LMB is not affected by anoxia (Douglas et al., 2004; Ross et al., 2008; Gibbs et al., 2011). The efficacy and strong P-binding properties of LMB made it a promising candidate for application in Lake De Kuil, where anoxic events near the sediment occurred annually. Apart from the single application of this 'Flock & Lock' method in Lake Rauwbraken, no knowledge exists of its efficacy in stratified lakes subject to seasonal anoxia.

The present study provides information on the efficacy of the Flock and Lock method in the stratified Lake De Kuil, where it was applied in a modified form. Whereas in Lake Rauwbraken the LMB was applied at the lake's surface (Lürling and Van Oosterhout, 2013), in Lake De Kuil most of the LMB was applied through deep injection to improve positioning of the LMB on the lake's bottom and to prevent turbid waters due to surface application. Lake De Kuil is a recreational lake to which the WFD and BWD apply. The lake suffered from regular cyanobacterial blooms since the early '90s which led to violation of BWD standards resulting in swimming bans and issue warnings in most summers. A system analysis revealed no major water inflow, but only rain and groundwater and pointed towards periodic P mobilisation under anoxia in the deeper water and near the sediment supporting the cyanobacterial blooms (Witteveen and Bos, 2006). A previous attempt to mitigate the nuisance caused by *Planktothrix rubescens* in Lake De Kuil was undertaken using artificial mixing from 1997 to 2005 (Ibelings et al., 1997). Supported by the intermittend mixing regime cyanobacterial nuisance persisted with *Microcystis* sp. and *Anabaena planctonica* (Witteveen and Bos, 2006). This experience shifted the focus to the reduction of sediment P-release. As the results of the Flock & Lock treatment of Lake Rauwbraken were promising (Van Oosterhout and Lürling, 2011), this treatment was selected for Lake De Kuil.

However, doubts within the managing water authority towards the safe use of aluminium (Al) in a recreational lake meant that no permit for the use of PAC in a low dose as flocculant could be obtained. Hence, the combined use of iron(III)chloride ($FeCl_3$) as flocculant and LMB as ballast and solid phase P-sorbent were chosen. The lake was treated in May 2009. We report the results of the combined treatment of $FeCl_3$ as flocculant and LMB as active barrier system in a whole-lake application over the period 2009–2014, for which we hypothesised that the treatment would precipitate cyanobacteria rapidly out of the water column, inhibit internal P-loading, and minimise cyanobacterial biomass in the following years.

2. Material and methods

2.1. Lake De Kuil

Lake De Kuil is located in the South western part of The Netherlands (N 51°37′22″; E 4°42′23″; Fig. 1). The lake was excavated in the 1950s to provide sand for the construction of the A16 motorway (Fig. 1). In 2000, one-third of the lake was filled with desalinated sea sand to allow for the widening of the motorway and the parallel high speed train track. Currently, the lake has a surface area of 6.7 ha, a maximum water depth of 9 m and an estimated water volume of 268,000 m^3. Reflecting its morphometry, the lake has characteristics of both shallow and deep stratifying lakes. The banks have partly been enforced with rocks. Submerged and emergent vegetation is not abundant. Using combined navigation (GPS) and sonar equipment from a boat a clear pattern of an irregular lake bedform was documented. Deeper holes (8–9 m) and shallower parts (5–7 m) alternate and reflect sand excavation activities, where excavation was stopped once a clay base was reached. A shallow part of the lake is being used as an official bathing site, while the remaining part of the lake is in use for angling. From 1992 onwards annually reoccurring cyanobacterial blooms have been reported, starting with *P. rubescens* blooms in the first years in spring followed by summer blooms of *Anabaena* ssp., *Woronichinia naegeliana* and *Microcystis aeruginosa*. The cyanobacterial blooms resulted in swimming bans and the issue of warnings in most of the years. To reduce bloom occurrence, in 1997 two wind-driven vertical water mixing devices were installed to induce destratification, however, because of their inefficiency the mixing was stopped in 2005. In 2008 the opening of the bathing season (May 1st) had to be postponed because of a cyanobacterial bloom, which prompted the authorities to investigate other management measures.

On average, the lake receives 61,750 m^3 water p.a. through direct precipitation and 14,128 m^3 p.a. through run-off from its catchment, while 50,170 m^3 p.a. is lost through evaporation and 25,708 m^3 p.a. leaves the lake through an outlet into a canal north of the lake (Supplementary information, Appendix A). Rates of

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