Water Research 97 (2016) 153–161

Contents lists available at ScienceDirect

Water Research

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

Long-term efficiency of lake restoration by chemical phosphorus precipitation: Scenario analysis with a phosphorus balance model

Michael Hupfer [a, *], Kasper Reitzel [b], Andreas Kleeberg [a, 1], Jörg Lewandowski [a]

[a] *Leibniz-Institute of Freshwater Ecology and Inland Fisheries Berlin, Müggelseedamm 301, D-12587 Berlin, Germany*
[b] *University of Southern Denmark Odense, Institute of Biology, Campusvej 55, DK-5230 Odense M, Denmark*

ARTICLE INFO

Article history:
Received 3 May 2015
Received in revised form
27 June 2015
Accepted 30 June 2015
Available online 6 July 2015

Keywords:
Sediment
Phosphorus retention
One-box model
Eutrophication
Phosphorus binding chemicals
Lake restoration

ABSTRACT

An artificial increase of phosphorus (P) retention in lakes with a long residence time and/or a large mobile sediment P pool by adding P binding chemicals can drastically shorten the time these lakes require to reach water quality targets. Suitable tools to optimize timing and extent of external and internal measures are lacking. The one-box model, a mass balance tool for predicting the P trend in the water under different management options was applied to highly eutrophic Lake Arendsee ($a = 5.14\ km^2$, $z_{max} = 49\ m$), Germany. Mass developments of blue green algae and increasing hypolimnetic oxygen deficiencies are urgent reasons for restoring Lake Arendsee. Detailed studies of P cycling and scenario analyses with the one-box model led to the following conclusions: i) immediate improvement of the trophic state is only possible by in-lake P inactivation because of the long water residence time (56 years); ii) a gradual external P load reduction, even if the effect is delayed, will assure the sustainability of the scheduled Al application beyond one decade; iii) a twofold precipitation reduces the risk of failure compared to a singular application with an overdose related to the relevant internal P pools.

1. Introduction

Phosphorus (P) as the limiting nutrient for primary production is often the driver of the ecological deterioration of temperate freshwater systems (Smith and Schindler, 2009; Withers et al., 2014). The introduction of surface water quality targets, and the legislative pressure for their implementation, e.g. as part of the EU Water Framework Directive (WFD), has enforced a debate for geoengineering using P-binding chemicals (PBC) in lake ecosystems (Spears et al., 2013a, 2014; Mackay et al., 2014). In the EU territory, about 36% of all reported WFD lakes (on a surface area basis) fail to meet the target of a 'good ecological status' (Spears et al., 2013a).

Many lake managers and scientists argue that external load reduction is the only sustainable way to improve water quality, and the precondition for supplemental in-lake measures (Mehner et al., 2002; Schauser and Chorus, 2007; Jensen et al., 2015). However, often the P load cannot be lowered to levels necessary to effectively control the trophic state within an acceptable time frame or budget. Additionally, the reduction of external P sources has not brought the expected improvement of water quality in many lakes because of processes in the catchment or in the lake itself that delay the response (Jeppesen et al., 2005; Schippers et al., 2006). The latter authors reported a study of a coupled catchment-shallow lake model considering the duration of buffer-related time delays. Results show that the most important buffer was the percolation of the soil layer, which may cause a delay of 150–1700 years depending on agricultural P surplus levels. The surface soil layer in contact with runoff water accounted for a delay of 5–50 years. However, the buffering capacity of the lake water was negligible whereas buffering in the lake sediment postponed the final lake equilibrium for several decades (Schippers et al., 2006). Therefore, PBCs are receiving more attention because the enrichment of mobile P in lake sediments has often been identified as the most important reason for the delay of water quality improvement after external P load reduction (Mehner et al., 2008; Søndergaard et al., 2013; Zamparas and Zacharias, 2014; Jensen et al., 2015).

In general, the 'good ecological status' can be achieved within an appropriate time frame by implementing internal measures into lake management concepts as follows: first, by rapidly decreasing available P in water and sediment (Mackay et al., 2014); second, by creating a positive feedback mechanism (Benndorf, 2008; Schallenberg and Sorrell, 2009) leading to self-stabilization of the

---

* Corresponding author.
E-mail address: hupfer@igb-berlin.de (M. Hupfer).
[1] Now at: State Laboratory Berlin–Brandenburg, Kleinmachnow, Germany.

http://dx.doi.org/10.1016/j.watres.2015.06.052
0043-1354/

lake ecosystem at the desired quality, e.g. formation of a macrophyte-dominated clear water state; and third, by preventing negative symptoms of a too high trophic state (Uhlmann et al., 2011). Benndorf (2008) argued that internal restoration techniques could partly compensate excessive external loads, and simultaneously decrease the cost of reaching quality targets since internal measures could be cheaper and faster than external measures for the equivalent P mass reduction. The point sources and the internal P are easier to control than the non point sources. It is not always obvious whether control measures should focus on reducing external or internal P loads, or whether both should be attempted, and the PBC doses required to achieve objectives need to be resolved on a case-by-case basis (Pilgrim et al., 2007).

The addition of PBCs promotes geochemical conditions which increase the net sink function of sediments by enhancing P sedimentation rates and/or decreasing P release rates. New substances and mixtures with improved characteristics have been designed and tested (Hickey and Gibbs, 2009; Spears et al., 2013b; Lürling and Oosterhout, 2013) but all of these substances are defined by a finite P binding capacity under given environmental conditions. Under consideration of the acid buffer capacity and alkalinity of the water, respectively, the necessary dose is often determined by the P pool in the water. But the retrospective evaluation of chemical inactivation measures has only shown a weak relation between the dose per unit water volume or area and the long-term effects (Welch and Cooke, 1999; Smeltzer et al., 1999; Huser et al., 2011). An increasing number of recent studies include the mobile P pool in the sediment (Rydin and Welch, 1999; Reitzel et al., 2005; de Vicente et al., 2008). Therefore, special attention is given to determining the available P pool pragmatically by assigning P fractions to temporary or permanent P pools (Rydin, 2000; Reitzel et al., 2005). Long-term improvements were observed when ‘a sufficient’ amount of PBC was added (e.g., Jensen et al., 2015). However, what is sufficient? The dose of PBC depends on the additional P binding capacity required over time, and thus from the development of the P balance including future P import. Empirical nutrient models like the Vollenweider Model (Vollenweider, 1976) are well proven tools for the management of eutrophic lakes. The statistical analysis of a large data set allows the prediction of P concentration and trophic state under a new steady state after external P load reduction or estimations of critical threshold values for the external P loading. However, this model does not explicitly include P retention in the sediment. The development during the transitional phase after restoration, adaptation time after external P load reduction and the impact of internal measures cannot be estimated with this kind of models. Contrary to this, mechanistic models based on the nutrient mass balances can be used to evaluate the impact of external and internal measures on the P development (Schauser and Chorus, 2007; Wauer et al., 2009; Grüneberg et al., 2011).

We use the highly eutrophic Lake Arendsee, North Germany, with a long water residence time, as a case study to predict the future P concentration following a planned P inactivation measure. Experiences with the application of PBCs in a lake as large as L. Arendsee, which is three times larger than Lake Delavan, USA (46.4×10^6 m^3), the largest lake treated by PBC to date, are not reported in the scientific literature (Huser et al., 2016).

The main objective of the present study is to provide a simple reliable tool for lake managers to optimize the interplay between external and internal measures for decreasing P availability in the water. The one-box model (Gächter and Imboden, 1985; Sas, 1989) was applied in order to: i) predict the speed and sustainability of external P load reduction versus internal P inactivation, ii) determine the optimal timing and dose of a PBC treatment, and iii) evaluate the effects of single dosage (equivalent to the internal P pools) compared to overdosage in the form of singular or repeated application under different P load reduction scenarios. We use scenario analyses to determine the necessary P fixation capacities over time as the basis for selecting an appropriate PBC.

2. Methods

2.1. Study site

Lake Arendsee (area 5.14 km^2, max. depth 49 m, mean depth 29 m) is situated in Northern Germany (52°53′21″ N, 11°28′27″ E) (Hupfer and Lewandowski, 2005). This dimictic hard water lake was originally fed solely by groundwater. Nowadays, four ditches draining adjacent agricultural fields additionally discharge into the lake and an artificial runoff channel transports water out of the lake (Meinikmann et al., 2015). At least since the middle of the last century, the lake has been strongly eutrophied (Scharf, 1998). The lake volume weighted total P (TP) concentration averaged 184 ± 7 µg L^{-1} (2005–2014, n = 10); the mean epilimnetic TP concentration during growing season was 96 ± 16 µg L^{-1}. The water quality is impaired by occasional low transparency with Secchi depth falling below 1 m and mass developments of phytoplankton dominated by cyanobacteria such as *Planktothrix rubescens*, (DC. Ex Gomont); or diazotrophic *Anabaena flos-aquae*, Bory de St.-Vincent and *Aphanizomenon flos-aquae*, (L.) during summer. The assessment based on the phytoplankton community has indicated a 'bad ecological status' so that the demand of the EU WFD for a good ecological status cannot be achieved at present. Additionally, dissolved oxygen (O_2) in the hypolimnion at the end of summer stratification has continuously decreased over the last four decades (Shatwell et al., 2013). The volume-weighted O_2 concentration between 20 and 48 m decreased from 4.76 ± 0.80 mg O_2 L^{-1} (1976–1980) to 1.83 ± 0.85 mg O_2 L^{-1} (2010–2014). Simultaneously, the upper border of the layer with concentration less than 2 mg O_2 L^{-1} shifted upwards from 42.4 ± 2.9 m to 33.3 ± 2.6 m water depth.

The above-ground catchment area (29.5 km^2) is dominated by agriculture (52.1%) and forestry (30.6%). The town Arendsee is situated directly on the south west shore (Fig. 1). The sum of the different, separately determined external P sources was 1560 kg yr^{-1} (0.303 g m^{-2} yr^{-1}; Meinikmann et al., 2015). More than 50% of this total P load is imported by groundwater enriched in P while passing below the town Arendsee. The recent anthropogenic P input via groundwater is one order of magnitude higher than the estimated input based on natural background P concentrations. According to Meinikmann et al. (2015), the P load in groundwater is highest followed by atmospheric deposition (19%), water fowl (maximum 13%), and drainage from agriculture (12%). Previous in-lake restoration measures in Lake Arendsee were not successful. Hypolimnetic withdrawal (1976–1990) and the capping of profundal sediments by mechanical resuspension of calcareous mud from the littoral (autumn 1995) have not shown any significant decrease of P (Hupfer et al., 2000). The current restoration intention aims to decrease the mean TP concentration at least to 60–80 µg L^{-1} (based on German guidelines for the implementation of WFD) so that P-limiting conditions for phytoplankton growth will prevail during the vegetation period.

2.2. Lake water phosphorus investigations

Lake Arendsee has been monitored since 1976. The P balance was calculated using TP concentrations in water samples taken at 0, 5, 10, 15, 20, 30, 40, 45 and 48 m depth (see Hupfer and Lewandowski, 2005).