Editorial – A critical perspective on geo-engineering for eutrophication management in lakes

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ABSTRACT

Eutrophication is the primary worldwide water quality issue. Reducing excessive external nutrient loading is the most straightforward action in mitigating eutrophication, but lakes, ponds and reservoirs often show little, if any, signs of recovery in the years following external load reduction. This is due to internal cycling of phosphorus (P). Geo-engineering, which we can here define as activities intervening with biogeochemical cycles to control eutrophication in inland waters, represents a promising approach, under appropriate conditions, to reduce P release from bed sediments and cyanobacteria accumulation in surface waters, thereby speeding up recovery. In this overview, we draw on evidence from this special issue *Geoengineering in Lakes*, and on supporting literature to provide a critical perspective on the approach. We demonstrate that many of the strong P sorbents in the literature will not be applicable in the field because of costs and other constraints. Aluminium and lanthanum modified compounds are among the most effective compounds for targeting P. Flocculants and ballast compounds can be used to sink cyanobacteria, in the short term. We emphasize that the first step in managing eutrophication is a *system analysis* that will reveal the main water and P flows and the biological structure of the waterbody. These site specific traits can be significant confounding factors dictating successful eutrophication management. Geo-engineering techniques, considered collectively, as part of a tool kit, may ensure successful management of eutrophication through a range of target effects. In addition, novel developments in modified zeolites offer simultaneous P and nitrogen control. To facilitate research and reduce the delay from concept to market a multi-national centre of excellence is required.

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1. Introduction

Human activities have resulted in enrichment of surface waters with nutrients, mainly nitrogen (N) and phosphorus (P). This cultural eutrophication has become a worldwide water quality issue (Smith and Schindler, 2009) and is recognised by scientists as the most important water quality problem (Downing, 2014). One of the symptoms of eutrophication is excessive phytoplankton growth, mainly cyanobacteria, which may cause nuisance blooms (Carpenter et al., 1998). Such blooms have negative consequences for ecosystem functioning and ecosystem services. Cyanobacterial blooms can obstruct the use of lakes, ponds and reservoirs as sources of drinking water, agricultural irrigation, fishing, industry water and recreation (Carmichael, 2001; Codd et al., 2005; Smith and Schindler, 2009) resulting in severe economic costs (Steffensen, 2008; Dodds et al., 2009). Thus, controlling eutrophication and mitigating nuisance cyanobacteria is an essential task.

Reducing excessive external nutrient loading is in principal the first adaptive management measure (Cooke et al., 2005). External load reduction may cause desired changes in lakes, but often little, if any, signs of recovery are observed in the years following external load reduction (Jeppesen et al., 1991). The main process responsible

for maintaining symptoms of eutrophication following catchment management is internal cycling of P. The in-lake P is released from a sediment pool which accumulated during the period of high external loading (Cooke et al., 2005). This internal P loading can delay lake recovery for decades (Søndergaard et al., 1999; Cooke et al., 2005; Fig. 1A) and it can, therefore, be necessary not only to reduce external P-loading, but also to mitigate the effects of internal P cycling from the sediment. Here, geo-engineering approaches, which are defined as the manipulation of biogeochemical processes (commonly targeting P) using materials to achieve a desired chemical and/or ecological response (Spears et al., 2014), represent a suite of tools with which water quality can be improved in the short term, thereby speeding up recovery (Fig. 1B).

2. Chemical P inactivation

With increasing population growth and resulting environmental change, the abatement of P inevitably requires in-lake interventions. Reducing external P load to lakes will generally be insufficient to mitigate nuisance eutrophication symptoms, especially in the short term, as those actions are predominantly tackling manageable point sources only (Carpenter et al., 1998). Non-point
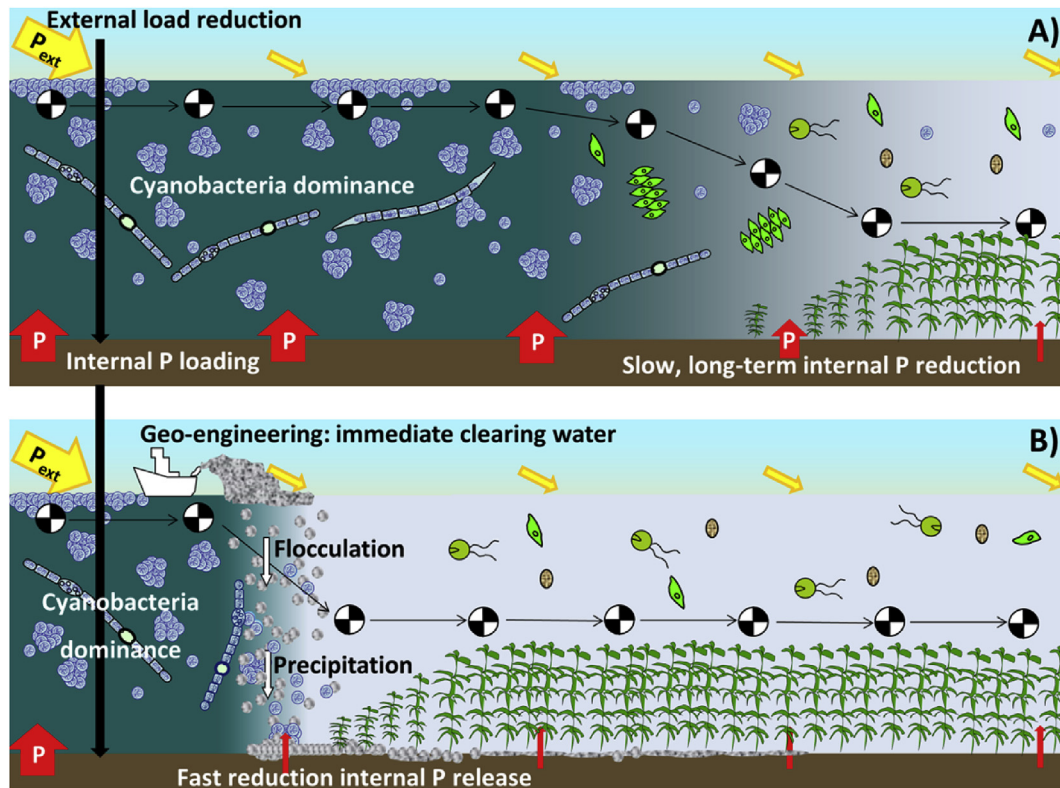
Fig. 1. Eutrophic lake with a delayed recovery in water quality (diminishing toxic cyanobacteria blooms) after external P load reduction due to eutrophication stabilizing internally stored P (upper panel A) and geo-engineering speeding up recovery through precipitation of water column P and cyanobacteria and chemical P fixation in the sediment (Panel B). ⬤ indicates the Secchi depth as a measure of water clarity.

sources from P saturated soils and ground water together with in-lake P cycling may limit recovery for decades to centuries (Carpenter, 2005; Jarvie et al., 2013). Hence, in-lake geo-engineering tools to specifically counteract diffuse groundwater P inflow and to constrain internally stored P are attractive additional measures.

There is a wealth of literature on PO_4-P sorbents ranging from metal salts, minerals, clays, fabricated oxides, layered double hydroxides and modified clays to industrial waste products, amongst others (see Supplementary information Table S1). These products encompass a wide range of P adsorption capacities from less than 1 mg P g^{-1} sorbent to more than 100 mg P g^{-1} sorbent (Table S1). When comparing the P adsorption capacities of different products in view of lake restoration, several additional aspects should also be taken into consideration. For successful field application, the P-sorbent should not only possess an affinity to adsorb P and to retain its adsorption capacity under naturally occurring conditions, but it should also be safe, cheap and easy to prepare and use. These criteria render many seemingly promising P-sorbents virtually inapplicable. For instance, layered double hydroxides with high phosphate adsorption capacities (47–71 mg g^{-1}, Jiang and Ashekuzaman, 2014), porous $Pr(OH)_3$ nanowires (129 mg g^{-1}, Tang et al., 2014), binary oxides (35 mg g^{-1}, Li et al., 2014; 12 mg g^{-1}, Long et al., 2011), and ceramic biomaterials (14 mg g^{-1}, Chen et al., 2014) are too elaborate to manufacture and too expensive to be applied at the ecosystem scale. Other materials, such as red mud (114 mg g^{-1}, Li et al., 2006), may come with toxicity issues (Misík et al., 2014). Materials may also exhibit far less P adsorption under natural conditions than their theoretical maximum as determined in a laboratory setting, which further limits their usefulness. La-modified zeolite has reduced P-

adsorption at pH slightly above 8, presumably through competition with hydroxyl ions (Ning et al., 2008), iron impregnated coir pith had high P-adsorption capacity (71 mg g^{-1}) at pH 3, but P-removal dropped to 20–30% at pH 8 (Krishnan and Haridas, 2008), while Al-pillared smectites expressed P-adsorption capacities of 20–27 mg g^{-1} at pH 3–4, but of only 5–7 mg g^{-1} at pH 6–7 (Kasama et al., 2004). Higher pH values are quite common in shallow eutrophic waterbodies, especially during periods of high primary productivity, and thus binding capacity at realistic pH values need to be better quantified.

Several studies have reported laboratory based comparisons of the PO_4-P adsorption maxima of tested materials with those of products in the literature, basing claims on material performance on unrealistic, or at times generally qualitative, comparisons (e.g., Zamparas et al., 2013; Li et al., 2014; Tang et al., 2014; Xie et al., 2014, 2015). However, comparing results from different studies should be done with caution as different conditions can have pronounced effects on the reported P-adsorption values, and these effects may be site- and material-specific.

In general, Fe-based P-sorbents should only be considered for use under aerobic conditions (i.e. redox potential >200 mV), where Fe-modified sorbents act, most likely, through exchange of hydroxide (OH^-) with phosphate ($H_2PO_4^-$) (Cooke et al., 2005). In contrast, under anoxia (i.e. <200 mV) reduction of Fe–P complexes will result in release of phosphate. This also holds true for zero-valent-iron (ZVI) that may express extremely high P-sorption capacity (Table S1), but of which the anaerobic corrosion product is soluble Fe^{2+} (Su and Puls, 2003). Low redox conditions are common in the hypolimnion and near or in the sediments of eutrophic lakes and reservoirs (Boström et al., 1988). Al- or La-modified clays do not suffer from redox sensitivity and block sediment P release equally