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Review

Sediment nutrients, ecological status and restoration of lakes

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ABSTRACT

Phosphorus (P) is the main nutrient that causes eutrophication in fresh waters. The majority of P in lake ecosystems is usually stored in the bottom sediment, hence P cycling from the sediment into the water column can significantly and negatively impact water quality. However, sediment nutrients are not taken into account, for instance, in the ecological status assessment determined by the European Water Framework Directive. This encourages lake managers to improve the water quality at the expense of the sediment; for example, chemical inactivation of P has been applied to the sediment in numerous lakes for rapid water quality improvement. While this may generate immediate results, inactivation of sediment P may in fact delay the long-term recovery of lake ecosystems and inhibit the re-use of nutrients. In some specific cases, these rapid restoration efforts that compromise sediment quality are justified. Nevertheless, we should aim for a general strategy that can promote permanent recovery of lake ecosystems — including their sediments. The support for such restoration activities may be difficult to find, since the tangible outcome is realized only after long periods of time.

Contents

1. Introduction

Phosphorus (P) is the main nutrient that controls the productivity of fresh waters, thus excessive external loading of P causes eutrophication problems (Schindler, 2012). The majority of P in lake ecosystems is usually stored in the bottom sediment, which can be recycled into the water column by various mechanisms (Pettersson, 1998; Søndergaard et al., 2003). While large-scale removal of sediment is one way to reduce external P loading for lake restoration, it is rarely possible due to the high cost and difficulties attributed to the large disposal areas needed for the removed sediment (Peterson, 1982; Cooke et al., 2005). Therefore, instead of nutrient removal, most lake restoration methods aim to simply diminish the flux of P from the sediment to the water. For instance, chemical inactivation of P has been used as a restoration tool in a large number of eutrophic lakes (Cooke et al., 2005; Huser et al., 2016). The chemical methods use an inactivation agent (e.g. aluminum (Al) or iron (Fe) salt or lanthanum (La) - amended clay)), which is added to the lake in order to bind P to the sediment. This decreases the P concentration in the water and increases the sorption capacity of the sediment, thus decreasing the overall recycling of sediment P to the water column (Søndergaard et al., 2003; Cooke et al., 2005). Similarly, other frequently used

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restoration methods such as artificial aeration and oxygenation also often aim to diminish the flux of P from the sediment to the water, as P is sorbed to Fe under oxidized conditions and can hence be retained in the sediment (Beutel and Horne, 1999; Bormans et al., 2016). On the other hand, both Fe and sorbed P return into solution under anoxic conditions (e.g. Søndergaard et al., 2003).

This article aims to highlight why future research efforts should focus on developing restoration methods that target the removal of P from lakes and facilitate the re-use of P, rather than aiming to retain P in the sediment.

2. Sediment nutrients, ecological status assessment and pressure for restoration

Inactivation of P through chemical methods has been applied to lake restoration for decades (e.g. Cooke et al., 2005), yet the interest in such methods still continues to increase. Indeed, chemical lake restoration methods are being applied all over the world, including Africa, Asia, Australia, Europe, New Zealand and North America (Liu et al., 2009; Egemose et al., 2010; Zamparas and Zacharias, 2014; Xue and Lu, 2015; Huser et al., 2016). This may indicate the improvement of treatment chemicals, but also reflects the desire for rapid water quality improvement and requirements set by public authorities. A good example is the European Water Framework Directive (WFD). According to the WFD set in 2000, all waters within the European Union (EU) were required to be in good ecological status by 2015, with extensions by 2021 or 2027. As a result, rapidly acting chemical methods are being used to achieve this WFD water quality criteria on schedule (Egemose et al., 2010; Zamparas and Zacharias, 2014).

According to the WFD, the ecological status of lakes is determined through hydro-morphological conditions, physical-chemical water quality, as well as through phytoplankton, zoobenthos, macrophyte and fish communities, with criteria determined separately for various lake types (Søndergaard et al., 2005). However, nutrients in the sediment are not taken into account, in spite of the ample studies that have confirmed the strong effect of sediment nutrients on the water quality – and thus the biotic communities – of lakes (Nürnberg, 1991, 2009; Søndergaard et al., 2003; Tammeorg et al., 2017).

While some fractions of P in the sediment are permanently buried, others are mobile (exchangeable) and can recycle back into the water column, for instance by diffusion (e.g. Carignan and Flett, 1981; Rydin, 2000). Loosely sorbed organic and inorganic fractions of P, Fe-bound P, as well as organic P in the non-reactive NaOH extractable P fraction are considered mobile and can amount to a large percentage of the total P in the sediment (Carignan and Flett, 1981; Rydin, 2000; Søndergaard et al., 2003; Reitzel et al., 2005). Internal P cycling that reduces the water quality and delays the recovery of eutrophicated lakes originates from the mobile P pool (Søndergaard et al., 2003). Therefore, some authors have reinforced the perspective that sediments are an essential part of aquatic ecosystems, and should therefore be given a stronger role in the WFD classification system (Brils, 2008).

3. Downside of rapid lake restoration

Classification criteria always include compromises, and it is not possible to include all regulatory factors. Costs of monitoring the chosen parameters must also be taken into account. Importantly, when sediment P is ignored, it is possible that the ecological status of a lake can be classified as high (i.e. indicating minimum anthropogenic impact), when in fact the sediment represents a very different status. Therefore, it is possible to conclude that the use of chemical P inactivation accelerates the recovery of lakes from eutrophication (Reitzel et al., 2005). Consequently, the view that the sediment P can be isolated from the rest of the lake ecosystem inevitably encourages lake managers to improve the water quality at the expense of the sediment (Egemose et al., 2010). Nevertheless, Carpenter et al. (2001) stated that if the concentration of sediment P in relation to water P is high enough, the system will always move back to the turbid-water state. Thus, by enriching the sediment with P, the water quality may be immediately improved at the expense of water quality in the future. Accordingly, in most cases the effects of chemical treatments are temporary. Although the effects can last for decades, usually the longevity is much shorter (Cooke et al., 2005; Huser et al., 2016). The difficulties to inhibit the internal P loading from the sediment are reflected also in the weak effects of artificial aeration. Despite the often insignificant effects on surface water quality, aeration is used frequently due to its functional versatility and seemingly unproblematic applicability (Salmi et al., 2014; Kuha et al., 2016; Schönach et al., 2017).

Overall, most attempts to restore eutrophic lakes only produce temporary effects, and few lakes have been successfully restored to the clear-water state after turning turbid (Osgood, 2000; Carpenter et al., 2001; Søndergaard et al., 2007). However, the major goal in restoration is that the restored ecosystem does not require further interventions to be sustainable (Suding and Gross, 2006). Additionally, P is a valuable natural resource with a decreasing availability, hence there is a growing concern about the scarcity of mineable P resources for crop production (Elser and Bennett, 2011; Neset and Cordell, 2012). To prevent the exhaustion of the reserves of phosphate rock, there is a clear need to ensure the efficient recycling of P (Dawson and Hilton, 2011). This aspect also argues against the strategy of enriching lake sediments with P, and serves as a reminder that burying P into sediment layers is not sustainable (Zamparas and Zacharias, 2014).

4. Time scales of restoration

Each lake must be studied separately. Indeed, there are cases where rapid restoration efforts that compromise sediment quality are justified. Continuous management efforts with short-lived results can be the best strategy, for instance, in drinking water supply lakes and reservoirs and in landscapes where there are only a few lakes in good condition (Cooke and Kennedy, 2001; Hanson et al., 2017). On a larger scale, however, we should aim for a strategy that can lead to permanent improvement in the status of lake ecosystems, including their sediments. For example, methods that could potentially be used to remove and recycle P accumulated in lake sediments include hypolimnetic withdrawal (Nürnberg, 2007; www.helsinki.fi/en/researchgroups/lake-ecosystem-dynamics). This method involves pumping or siphoning P-rich water from the anoxic deep water of a eutrophic lake, and trapping P before leading the water downstream or back into the lake. As reminded by Nürnberg (1991), internal P load from the sediment into the water is a self-purification process. Thus, more effort should be put towards developing methods that would use this internal flux for removing P from the ecosystem, instead of methods that aim to inhibit the flux. Other inadequately studied methods for removing P include novel sediment removal techniques (https://seabasedmeasures.eu/pilots/) and removal of organisms that exploit sediment P, such as macrophytes (Asaeda et al., 2000; James et al., 2002), benthivorous fish (Drenner et al., 1996; Bernes et al., 2015) and algae (Xie et al., 2003; Brandenburg et al., 2008).

Most of the methods based on P removal do not improve the water quality as rapidly as those methods that enrich the sediment with P. This creates a perception problem, since the temporal scales of ecosystem responses can exceed the scales over which humans are willing to understand (Power, 1999). Moreover, there are also societal and political dimensions to be considered in restoration and management. Hence, support for restoration activities may be difficult to find when their outcome is expected after decades – even though it is unrealistic to assume that disturbances caused by decades of environmental stress (e.g. eutrophication) can be corrected in a much shorter time (Keller et al., 1999; Power, 1999). Indeed, restoration often takes a much longer time than the time of degradation (Moreno-Mateos et al., 2012; Lake, 2013). Therefore, long-term restoration methods and projects should be encouraged, and sediment nutrients should be taken into account when assessing the ecological status of lakes. This would likely alter the ecological status classification of many lakes, but would also give a more realistic overview about the situation in these lakes, and the time scales needed for their restoration.

5. Conclusions

- Most methods that are frequently used in the restoration of eutrophicated lakes aim to retain P in the sediment;
- Enriching the sediments with P is unsustainable, because it can delay the long-term recovery of lake ecosystems, and inhibits the re-use of P;
- The current demands for rapid improvement of water quality encourage restoration of lakes at the expense of the sediment quality;
- An example of such a demand is the classification system of the ecological state of lakes in the EU;
- Long-term restoration methods and projects should be encouraged, and sediment nutrients should be taken into account when assessing the status of lakes

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Asaeda, T., Trung, V.K., Manatunge, J., 2000. Modeling the effects of macrophyte growth and decomposition on the nutrient budget in shallow lakes. Aquat. Bot. 68, 217–237.

Bernes, C., Carpenter, S.R., Gårdmark, A., Larsson, P., Persson, L., Skov, C., Speed, J.D.M., Van Donk, E., 2015. What is the influence of a reduction of planktivorous and benthivorous fish on water quality in temperate eutrophic lakes? A systematic review. Environ. Evid. 4, 7.

Brandenburg, W.A., Smit, B.L., Neeteson, J.J., 2008. Marine algal biomass for energy regeneration and possible phosphorus recovery. In: Proc, vol. 634. Int. Fertil. Soc., York, UK.

Beutel, M.W., Horne, A.J., 1999. A review of the effects of hypolimnetic oxygenation on lake and reservoir water quality. Lake Reservoir Manag. 15, 285–297.

Bormans, M., Maršálek, B., Jančula, D., 2016. Controlling internal phosphorus loading in lakes with physical methods to reduce cyanobacterial blooms: a review. Aquat. Ecol. 50, 407–422.

Brils, J., 2008. Sediment monitoring and the European water framework directive. Ann. Ist. Super Sanitá 44, 218–223.

Carignan, R., Flett, R.J., 1981. Postdepositional mobility of phosphorus in lake sediments. Limnol. Oceanogr. 26, 361–366.

Carpenter, S.R., Walker, B., Anderies, J.M., Abel, N., 2001. From metaphor to measurement: resilience of what to what? Ecosystems 4, 765–781.

Cooke, G.D., Kennedy, R.H., 2001. Managing drinking water supplies. Lake Reservoir Manag. 17, 157–174.

Cooke, G.D., Welch, E.B., Peterson, S.A., Nichols, S.A., 2005. Restoration and Management of Lakes and Reservoirs, third ed. Taylor & Francis, Boca Raton, London, ISBN 1-56670-625-4.

Dawson, C.J., Hilton, J., 2011. Fertiliser availability in a resource-limited world: production and recycling of nitrogen and phosphorus. Food Policy 36, 514–522.

Drenner, R.W., Smith, J.D., Therkeld, S.T., 1996. Lake trophic state and the limnological effects of omnivorous fish. Hydrobiologia 19, 213–223.

Egemose, S., Reitzel, K., Andersen, F.Ø., Flindt, F.R., 2010. Chemical lake restoration products: sediment stability and phosphorus dynamics. Environ. Sci. Technol. 44, 985–991.

Elser, J., Bennett, E., 2011. A broken biogeochemical cycle. Nature 478, 29–31.

Hanson, M.A., Herwig, B.R., Zimmer, K.D., Hansel-Welch, N., 2017. Rehabilitation of shallow lakes: time to adjust expectations? Hydrobiologia 787, 45–59.

Huser, B.J., Egemose, S., Harper, H., Hupfer, M., Jensen, H., Pilgrim, K.M., Reitzel, K., Rydin, E., Futter, M., 2016. Longevity and effectiveness of aluminum addition to reduce sediment phosphorus release and restore lake water quality. Water Res. 97, 122–132.

James, W.F., Barko, J.W., Eakin, H.L., Sorge, P.W., 2002. Phosphorus budget and management strategies for an urban Wisconsin Lake. Lake Reservoir Manag. 18, 149–163.

Keller, W., Gunn, J.M., Yan, N.D., 1999. Acid rain – perspectives on lake recovery. J. Aquatic Ecosyst. Stress Recovery 6, 207–216.

Kuha, J.K., Palomäki, A.H., Keskinen, J.T., Karjalainen, J.S., 2016. Negligible effect of hypolimnetic oxygenation on the trophic state of Lake Jyväsjärvi, Finland. Limnologica 58, 1–6.

Lake, L., 2013. Resistance, resilience and restoration. Ecol. Manag. Restor. 14, 1–5.

Liu, Y., Tian, K., Winks, K., 2009. Water eutrophication prevention by Phoslock flocculation and sediment capping reaction. 2009. In: International Conference on Environmental Science and Information Application Technology, vol. 1, pp. 349–352.

Moreno-Mateos, D., Power, M.E., Comin, F.A., Yockteng, R., 2012. Structural and functional loss in restored wetland ecosystems. PLoS Biol. 10 https://doi.org/10.1371/journal.pbio.1001247.

Neset, T.S.S., Cordell, D., 2012. Global phosphorus scarcity: identifying synergies for a sustainable future. J. Sci. Food Agric. 92, 2–6.

Nürnberg, G.K., 1991. Phosphorus from internal sources in the Laurentian Great Lakes, and the concept of threshold external load. J. Great Lakes Res. 17, 132–140.

Nürnberg, G.K., 2007. Lake responses to long-term hypolimnetic withdrawal treatments. Lake Reservoir Manag. 23, 388–409.

Nürnberg, G.K., 2009. Assessing internal phosphorus load – problems to be solved. Lake Reservoir Manag. 25, 419–432.

Osgood, R., 2000. Lake sensitivity to phosphorus changes. Lake Line 20, 9–11.

Peterson, S.A., 1982. Lake restoration by sediment removal. Water Resour. Bull. 18, 423–435.

Pettersson, K., 1998. Mechanisms for internal loading of phosphorus in lakes. Hydrobiologia 373/374, 21–25.

Power, M., 1999. Recovery in aquatic ecosystems: an overview of knowledge and needs. J. Aquatic Ecosyst. Stress Recovery 6, 253–257.

Reitzel, K., Hansen, J., Andersen, F.Ø., Hansen, K., Jensen, H., 2005. Lake restoration by dosing aluminum relative to mobile phosphorus in the sediment. Environ. Sci. Technol. 39, 4134–4140.

Rydin, E., 2000. Potentially mobile phosphorus in Lake Erken sediment. Water Res. 34, 2037–2042.

Salmi, P., Malin, I., Salonen, K., 2014. Pumping of epilimnetic water into hypolimnion improves oxygen but not necessarily nutrient concentrations in a lake recovering from eutrophication. Inland Waters 4, 425–434.

Schindler, D.W., 2012. The dilemma of controlling cultural eutrophication of lakes. Proc. Royal Soc. B. 279, 4322–4333.

Schönach, P., Tapio, P., Holmroos, H., Horppila, J., Niemistö, J., Nygrén, N., Tammeorg, O., Massa, I., 2017. Persistency of artificial aeration at hypertrophic Lake Tuusulanjärvi: a sociohistorical analysis. Ambio 46, 865–877.

Søndergaard, M., Jensen, J.P., Jeppesen, E., 2003. Role of sediment and internal loading of phosphorus in shallow lakes. Hydrobiologia 506–509, 135–145.

Søndergaard, M., Jeppesen, E., Jensen, J.P., Amsink, S.L., 2005. Water framework directive: ecological classification of Danish lakes. J. Appl. Ecol. 42, 616–629.

Søndergaard, M., Jeppesen, E., Lauridsen, T.L., Skov, C., Van Nes, E.H., Roijackers, R., Lammens, E., Portielje, R., 2007. Lake restoration: successes, failures and long-term effects. J. Appl. Ecol. 44, 1095–1105.

Suding, K.N., Gross, K.L., 2006. The dynamic nature of ecological systems: multiple states and restoration trajectories. In: Falk, D.A., Palmer, M.A., Zedler, J.B. (Eds.), Foundations of Restoration Ecology. Island Press, Washington D.C., pp. 190–209

Tammeorg, O., Möls, T., Niemistö, J., Holmroos, H., Horppila, J., 2017. The actual role of oxygen deficit in the linkage of the water quality and benthic phosphorus release: potential implications for lake restoration. Sci. Total Environ. 599–600, 732–738.

Xue, W., Lu, S., 2015. Effects of inactivation agents and temperature on phosphorus release from sediment in Dianchi Lake, China. Environ. Earth. Sci. 74, 3857–3865.

Xie, L., Xie, P., Li, S., Tang, H., Liu, H., 2003. The low TN:TP ratio, a cause or a result of Microcystis blooms? Water Res. 37, 2073–2080.

Zamparas, M., Zacharias, I., 2014. Restoration of eutrophic freshwater by managing internal loads. A review. Sci. Total Environ. 496, 551–562.