



Preface: Advances in phosphorus inactivation

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PREFACE



Preface: Advances in phosphorus inactivation

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ABSTRACT

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Experience from more than 4 decades of phosphorus inactivation research, projects, and follow up monitoring has led to improved understanding of mechanisms and results that enhance the ability of lake managers to control P availability in lake water and sediment. Recent advances derived largely from monitoring lakes treated with aluminum or lanthanum over an extended time have shed light on important factors in dose determination, binding efficiency, application processes, benefits of treatment, and duration of benefits. Advances are embodied in 10 articles in this issue of *Lake and Reservoir Management* that, along with important literature from the last 2 decades cited in those papers, documents improvement in our knowledge and application of P inactivation as a tool in lake management.

KEYWORDS

aluminum; lake management; lanthanum; P inactivation

Phosphorus (P) inactivation has been part of lake management for more than 4 decades, a logical extension from use of coagulants in water and wastewater treatment systems to remove a variety of impurities (Cooke et al. 2005). Salts of aluminum (Al), iron (Fe), and calcium (Ca) have been applied for many years, joined more recently by lanthanum (La). The primary use has been to inactivate P in surficial sediment to prevent release into the overlying water column (Cooke et al. 2005), but applications at lower doses to strip P from the water column or inactivate P in incoming storm water are becoming reliable maintenance techniques (Harper et al. 1999, Wagner 2017). Results from a combination of laboratory studies, experimental environmental applications, and monitoring of lake treatments enhance our understanding of P inactivation in lakes and further shape treatment technologies and protocols.

Al, Ca, Fe, and organic matter are the major, natural binders of P in sediment. Al and La have become the treatment binders of choice. Fe will release P under anoxic conditions and is limited to use in P inactivation programs in which oxygen is maintained by oxygenation systems (Engstrom 2005). Ca can be added to bind P in highly alkaline lakes (Murphy et al. 1993), but negative impacts on biota at high treatment pH limits

Ca applications. Nearly all of the applications of the last decade have involved Al or La.

This themed issue of *Lake and Reservoir Management* intends to capture some of the P inactivation advances of the last decade. The idea for this issue arose from a set of presentations made at the November 2015 international symposium of the North American Lake Management Society (NALMS) and a themed issue of *Water Research* (Volume 97) that led to more discussion and an expanded comprehension of P inactivation processes and results, including improved understanding of dose determination, binding efficiency, application processes, treatment benefits, and duration of benefits. Although more remains to be learned, P inactivation projects can be improved based on what we have learned in recent years.

Dose determination

Determination of the necessary dose for adequate P inactivation in sediment is complicated by sediment features, including the amount and forms of P targeted for inactivation, quantity of compounds that compete with P for binding sites (Huser and Pilgrim 2014, James and Bischoff 2015), sediment density that affects penetration of applied P binders (James 2017),

bioturbation that can increase the depth of mixing (Huser et al. 2016a, Welch et al. 2017a), and remaining P binding capacity over years after initial reactions (Huser 2017, Welch et al. 2017a). Empirically, it has been suggested that Al doses must be at least 10 times the targeted P mass (Jensen et al. 2015, Huser et al. 2016b). A minimum ratio of Al:P mass of 10:1 is supported by treatment results from Cape Cod, Massachusetts (Wagner et al. 2017), whereas higher Al:P ratios may be necessary to overcome interferences and inefficiencies in some lakes (Huser 2017, James 2017).

P inactivation seems to continue for multiple years after initial application (Lewandowski et al. 2003, Huser 2017, Welch et al. 2017a), suggesting that increased dose can enhance longevity of results. James (2017), however, found that a 150 g/m² dose of Al failed to penetrate far into the sediment of one lake, polymerizing at the surface and leaving much target P still available. The relationship between dose and frequency of application warrants consideration in treatment planning and long-term management of P in lakes.

Laboratory assays have been developed to allow determination of initial inactivation potential of any given Al dose to site specific sediment (Rydin and Welch 1999, Pilgrim et al. 2007, Wagner et al. 2017). Doses for La applications, as an amended bentonite clay mixture marketed as Phoslock, are also typically determined by laboratory assay (Meis et al. 2012, 2013). These assays are particularly helpful where the inactivation of P is not linearly proportional to the dose of binder because the percentage of targeted P that will be inactivated can be determined at any given dose. Translating dose into cost, the marginal cost of each increment of dose increase and can be evaluated and the internal P load reduction compared with project cost.

Actual doses of Al to lakes to inactivate mobile sediment P have ranged from 10 to 150 g/m² in projects covered in this issue (James 2017, Wagner et al. 2017), with an average close to 50 g/m². Doses to inactivate P in inflows or the water column of lakes are typically <10 mg/L (Pilgrim and Brezonik 2005, Wagner 2017). Doses of Phoslock to inactivate sediment P have ranged from 140 to 670 g/m² (Spears et al. 2016), while actual and planned application rates for Canadian lakes reported by Nürnberg (2017) ranged from 100 to 460 g/m². Doses of Phoslock for water column P stripping and supplemental sediment treatment were 190 g/m² in repeated applications during a 9-year study of a small bathing lake (Epe et al. 2017).

Binding efficiency

The binding efficiency of any binder is a critical aspect of treatment planning and varies with many factors, not all of which are well understood. Both Al and La will theoretically bind P at a 1:1 molar ratio, but interference from other elements can reduce that efficiency and obtaining accurate measurements is not easy. Whether the reaction is occurring in water or sediment affects binding efficiency as well. Tracking Al:P ratios in sediment following treatment has revealed that binding efficiency increases over time (Huser 2017, Welch et al. 2017a). The eventual Al:P ratio in treated sediment is usually <20:1, and often <10:1. Yet binding efficiency is not constant over the range of mobile sediment P mass (Huser and Pilgrim 2014, James and Bischoff 2015); cost per unit of P inactivated increases as mobile sediment P mass decreases.

The observed binding ratio for Phoslock (clay amended with La) to P in a range of waters from fresh to brackish has been reported at 100:1 to 200:1 by weight (Reitzel et al. 2013a). La is 5% of Phoslock by weight and has a molecular weight of 139 compared to P at 31, suggesting an La:P molar ratio of 1.1 to 2:1 for Phoslock applications to water. Assessed binding ratios for La:P in sediment have been higher (Reitzel et al. 2013b), with a range of 3.8:1 to 40:1 calculated from available data.

Despite uncertainty of binding ratios, they can be factored into application planning. Doses in successful Cape Cod treatments (Wagner et al. 2017) were 10 to 20 times the targeted P mass, consistent with the Al:P binding ratios predicted according to the Huser (2012) equation based on Al dose and slope. Underdosing impacts effectiveness and longevity, whereas overdosing affects efficiency and cost; achieving balance is a challenge, but we are gradually developing the tools to enhance treatment planning.

Application processes

P binders have traditionally been applied from a barge moving over the target area (Cooke et al. 2005), with reactions occurring in the water column and after the applied material settles onto the sediment surface. Each Al product undergoes hydrolysis reactions when applied to a lake that lead to coagulation that includes P binding (Cooke et al. 2005). La is not a coagulant but reacts with soluble reactive P to form a hydrous

La phosphate called rhabdophane by ionic bond (Meis et al. 2013). Most Al applications involve injection of liquids that form a floc, whereas La is applied as part of an amended bentonite clay slurry (Phoslock). Applied Al or Phoslock is expected to settle from the water column in a matter of hours.

Lake applications for sediment treatment have generally been found to result in deposition to the target area of sediment, although some drift outside the target area is expected with any appreciable wind (Wagner et al. 2017, Welch et al. 2017b). Deposition to sediment has been assumed to result in reactions in the upper 4–10 cm of sediment, but the distribution of Al can be deeper (Welch et al. 2017a) or shallower (James 2017), and follow up core sampling has been necessary to evaluate penetration of Al into sediment. The vertical distribution of La in sediment after treatment seems similar to that of Al (Dithmer et al. 2016).

It has also been determined that Al may not stay in the treatment area if the bottom has a significant slope (Huser 2017). Novel application of Al described by Schütz et al. (2017) involved injection of the Al into the sediment, minimizing drift or focusing and potentially controlling at least the initial depth of mixing within the sediment.

Harper et al. (1999) pioneered storm water inflow treatments to inactivate incoming P in Florida, and systems that pump Al into an inflow pipe, ditch, or stream have become more widespread (Pilgrim and Brezonik 2005, Wagner 2017). In some cases, a retention pond is provided to capture Al floc before it enters the lake, whereas in others the floc is allowed to enter the lake and settle onto target sediments where further P inactivation can occur.

Water column applications of P binders have been used as “maintenance” treatments, applied when needed to strip P from the water column to minimize algae blooms (Brattebo et al. 2017, Epe et al. 2017). These treatments can be conducted with the same equipment as applications targeting the sediment or can be coupled with circulation systems that can mix the P binder if delivered to a diffuser in a feedline. The target Al:P ratio of between 10:1 and 20:1 used for most sediment treatments seems applicable to inflow and water column treatments as well (Brattebo et al. 2017, Wagner 2017). The ratio of Phoslock to P in water column treatments by Epe et al. (2017) is estimated at about 300:1 (15:1 for just the La) by weight, although extra Phoslock was applied to further inactivate P in sediment.

Treatments targeting the water column should be conducted in advance of algae blooms for best results. Al and La do not directly kill algae but instead limit P availability; treating after a bloom has formed is not as effective in the short term but may still produce acceptable results, and those results may improve over time (Nürnberg and LaZerte 2016).

Benefits of treatment

In lakes where internal loading of P is a significant source for algae, inactivation of mobile P in surficial sediment has proven to reduce algae biomass in general and limit blooms of cyanobacteria in particular (Cooke et al. 2005, Wagner et al. 2017). The impact on nitrogen (N) from P inactivation treatments is less, although more loss of inorganic N is reported for Phoslock (Epe et al. 2017) than for Al (Wagner et al. 2017). N:P ratios in lakes have been raised by Al (Wagner et al. 2017) or La (Douglas et al. 2016) treatments, favoring algae other than cyanobacteria.

P-stripping maintenance treatments for the water column or inflows may provide acceptable results, even when external sources have not been adequately controlled (Brattebo et al. 2017, Epe et al. 2017, Wagner 2017). Watershed management to control the sources of P would be preferable, but is not always feasible because of cost, jurisdictional issues, or competing management goals (Rissman and Carpenter 2015, Huser et al. 2016c). Maintenance treatment can provide more immediate relief than watershed management and may be used as an interim measure until watershed management can be fully implemented.

An additional benefit from P inactivation is reduced oxygen demand. Cape Cod lakes experienced reduced oxygen demand in the hypolimnion after Al treatment (Wagner et al. 2017). Sediment oxygen demand is not completely countered by such treatments, but the lower deposition of decaying algae results in lower oxygen demand, sometimes preventing complete hypolimnetic anoxia during stratification and providing suitable habitat for coldwater fish.

Duration of benefits

The longevity of benefits for Al treatments for sediment P inactivation described by Welch and Cooke (1999) were revisited in an expanded analysis by Huser et al. (2016b). Duration of reduced P and chlorophyll *a* with increased water clarity were found to average about

6 years for unstratified lakes and 21 years for stratified lakes. Failures relate mainly to inadequate dosing or continued external inputs of a magnitude much greater than the internal load. The duration of benefits from Phoslock treatments is not as well known, simply because it has not been available as long as Al products, but available reviews (Copetti et al. 2016, Dithmer et al. 2016, Spears et al. 2016) suggest many of the same benefits as Al treatments for a decade or more so far. The duration of benefits for inflow and water column treatments is shorter than for sediment P inactivation, usually ~1–3 years (Epe et al. 2017, Wagner 2017).

The mechanisms by which benefits are curtailed are now better understood. Certainly continued inputs from watersheds are important, and gradual burial of the treated sediment will lead to renewed internal loading, but that process seems to be slow in stratified lakes and where the watershed:lake area ratio is low (Huser et al. 2016b). Two internal mechanisms that control internal P loading after treatment are upward migration of P from below the inactivated zone in the sediment (Lewandowski et al. 2003, James 2017) and release from organic matter through decay (Jensen et al. 2015). Both can be important P sources and are likely to contribute in most lakes.

Conclusion

Many researchers and lake managers have contributed to the advancement of our knowledge of P inactivation over the last 2 decades, and those efforts are acknowledged and appreciated. Ongoing discussions and collaboration among the authors who contributed to this themed issue of Lake and Reservoir Management are expected to further our understanding. Continued monitoring of treated lakes will be important to provide data that will further characterize the range of results and their duration. Continued experimentation is important to elucidating mechanisms associated with results and eventual diminishment of benefits. There is indeed more to learn to allow best application of P inactivation in lake management.

Advancements to date, however, have allowed practitioners to better plan and execute P inactivation projects, and the papers in this issue exemplify those advancements. We have a reasonable sense for the range of effective doses and likely binding efficiency over time. Application techniques have been improved and negative impacts of treatments have been greatly reduced. Benefits have been documented and the

duration of benefits has been bracketed. We better understand how benefits eventually diminish and can plan for long-term management programs that enhance cost effectiveness. Although still not a mature science, P inactivation can be reliably used in lake management.

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References

- Brattebo SK, Welch EB, Gibbons HL, Burghdoff MK, Williams GN, Oden JL. 2017. Effectiveness of alum in a hypereutrophic lake with substantial external loading. *Lake Reserv. Manage.* 33:108–118.
- Cooke GD, Welch EB, Peterson SA, Nichols SA. 2005. Restoration and management of lakes and reservoirs. 3rd ed. Boca Raton (FL): Taylor & Francis.
- Copetti D, Finsterle K, Marziali L, Stefani F, Tartari G, Douglas G, Reitzel K, Spears BM, Winfried IJ, Crosa G, et al. 2016. Eutrophication management in surface waters using lanthanum modified bentonite: a review. *Water Res.* 97: 162–174.
- Dithmer L, Nielsen UG, Lüring M, Spears BM, Yasseri S, Lundberg D, Moore A, Jensen ND, Reitzel K. 2016. Responses in sediment phosphorus and lanthanum concentrations and composition across 10 lakes following applications of lanthanum modified bentonite. *Water Res.* 97:101–110.
- Douglas GB, Lüring M, Spears BM. 2016. Assessment of changes in potential nutrient limitation in an impounded river after application of lanthanum-modified bentonite. *Water Res.* 97:47–54.
- Engstrom DR. 2005. Long term changes in iron and phosphorus sedimentation in Vadnais Lake, Minnesota, resulting from ferric chloride addition and hypolimnetic aeration. *Lake Reserv. Manage.* 21:96–106.
- Epe TS, Finsterle K, Yasseri S. 2017. Nine years of phosphorus management with lanthanum modified bentonite (Phoslock) in a eutrophic, shallow swimming lake in Germany. *Lake Reserv. Manage.* 33:119–129.
- Harper HH, Herr JE, Livingston E. 1999. Alum treatment of storm water: the first ten sources. In: James W, editor. Modeling urban water systems. Guelph (Canada): Computational Hydraulics International. p. 159–180.
- Huser BJ. 2012. Variability in phosphorus binding by aluminum in alum treated lakes explained by lake morphology and aluminum dose. *Water Res.* 46:4697–4704.
- Huser BJ. 2017. Aluminum application to restore water quality in eutrophic lakes: Maximizing binding efficiency between

- aluminum and phosphorus. *Lake Reserv Manage.* 33:143–151.
- Huser BJ, Bajer PG, Chizinski CJ, Sorensen PW. 2016a. Effects of common carp (*Cyprinus carpio*) on sediment mixing depth and mobile phosphorus mass in the active sediment layer of a shallow lake. *Hydrobiologia.* 763:23–33.
- Huser BJ, Egemose S, Harper H, Hupfer M, Jensen H, Pilgrim KM, Reitzel K, Rydin E, Futter M. 2016b. Longevity and effectiveness of aluminum addition to reduce sediment phosphorus release and restore lake water quality. *Water Res.* 97:122–132.
- Huser BJ, Futter M, Lee JT, Perniel M. 2016c. In-lake measures for phosphorus control: the most feasible and cost-effective solution for long-term management of water quality in urban lakes. *Water Res.* 97:142–152.
- Huser BJ, Pilgrim KM. 2014. A simple model for predicting aluminum bound phosphorus formation and internal loading reduction in lakes after aluminum addition to lake sediment. *Water Res.* 53:378–385.
- James W. 2017. Phosphorus binding dynamics in the aluminum flocculation layer of Half Moon Lake, Wisconsin. *Lake Reserv Manage.* 33:130–142.
- James W, Bischoff J. 2015. Relationships between redox-sensitive phosphorus concentrations in sediment and the aluminum:phosphorus binding ratio. *Lake Reserv Manage.* 31:339–346.
- Jensen H, Reitzel K, Egemose S. 2015. Evaluation of aluminum treatment efficiency on water quality and internal phosphorus cycling in six Danish lakes. *Hydrobiologia.* 751:189–199.
- Lewandowski J, Schauser I, Hupfer M. 2003. Long-term effects of phosphorus precipitation with alum in hypereutrophic Lake Stüsser See (Germany). *Water Res.* 37:3194–3204.
- Meis S, Spears BM, Maberly SC, O'Malley MB, Perkins RG. 2012. Sediment amendment with Phoslock in Clatto Reservoir (Dundee, UK): investigating changes in sediment elemental composition and phosphorus fractionation. *J Environ Manage.* 93:185–193.
- Meis S, Spears BM, Maberly SC, Perkins RG. 2013. Assessing the mode of action of Phoslock in the control of phosphorus release from the bed sediments in a shallow lake (Loch Flemington, UK). *Water Res.* 47:4460–4473.
- Murphy T, Manning P, Prepas E, Babin J, Hall K. 1993. Developments in lake restoration in western Canada. *Can Water Res J.* 18:299–306.
- Nürnberg GK. 2017. Attempted management of cyanobacteria by Phoslock (lanthanum modified clay) in Canadian lakes: Water quality results and predictions. *Lake Reserv Manage.* 33:163–170.
- Nürnberg GK, LaZerte BD. 2016. Trophic state decrease after lanthanum-modified bentonite clay (Phoslock) application to a hyper-eutrophic polymictic urban lake frequented by Canada geese (*Branta canadensis*). *Lake Reserv Manage.* 32:74–88.
- Pilgrim KM, Brezonik PL. 2005. Treatment of lake inflows with alum for phosphorus removal. *Lake Reserv Manage.* 21:1–9.
- Pilgrim KM, Huser BJ, Brezonik PL. 2007. A method for comparative evaluation of whole-lake and inflow alum treatment. *Water Res.* 41:1215–1224.
- Reitzel K, Andersen FØ, Egemose S, Jensen HS. 2013a. Phosphate adsorption by lanthanum modified bentonite clay in fresh and brackish water. *Water Res.* 47:2787–2796.
- Reitzel K, Lotter S, Dubke M, Egemose S, Jensen HS, Andersen FO. 2013b. Effects of Phoslock treatment and chironomids on the exchange of nutrients between sediment and water. *Hydrobiologia.* 703:189–202.
- Rissman AR, Carpenter SR. 2015. Progress on nonpoint pollution: barriers and opportunities. *Daedalus.* 144:27–34.
- Rydin E, Welch EB. 1999. Dosing alum to Wisconsin Lake sediments based on in vitro formation of aluminum bound phosphate. *Lake Reserv Manage.* 15:324–331.
- Schütz J, Rydin E, Huser BJ. 2017. A newly developed injection method for aluminum treatment in eutrophic lakes: Effects on water quality and phosphorus binding efficiency. *Lake Reserv. Manage.* 33:152–162.
- Spears BM, Mackay EB, Yasseri S, Gunn ID, Waters KE, Andrews C, Cole S, De Ville M, Kelly A, Meis S, et al. 2016. A meta-analysis of water quality and aquatic macrophyte responses in 18 lakes treated with lanthanum modified bentonite (Phoslock). *Water Res.* 97:111–121.
- Wagner K. 2017. Phosphorus inactivation of incoming storm water to reduce algal blooms and improve water clarity in an urban lake. *Lake Reserv Manage.* 33:187–197.
- Wagner K, Meringolo D, Mitchell D, Moran E, Smith S. 2017. Aluminum treatments to control internal phosphorus loading in lakes on Cape Cod, Massachusetts. *Lake Reserv Manage.* 33:171–186.
- Welch EB, Cooke GD. 1999. Effectiveness and longevity of phosphorus inactivation with alum. *Lake Reserv Manage.* 15:5–27.
- Welch EB, Gibbons HL, Brattebo SK, Corson-Rikert HA. 2017a. Progressive conversion of sediment mobile phosphorus to aluminum phosphorus. *Lake Reserv Manage.* 33:205–210.
- Welch EB, Gibbons HL, Brattebo SK, Corson-Rikert HA. 2017b. Distribution of aluminum and phosphorus fractions following alum treatments in a large shallow lake. *Lake Reserv Manage.* 33:198–204.