Nutrient Inactivation with Alum: **What Has Worked and Why**

Shannon Brattebo, Eugene Welch, and Harry Gibbons

Alum has been one of the most successfully implemented and effective in-lake treatments to reduce internal loading of phosphorus (P). There have been over 250 documented or reported treatments in the world, nearly all in the U.S. Internal loading was reduced by 70-80% for the lakes studied (Cooke et al. 2005). Whole-lake water quality improved as well, if internal loading was the principal source of P driving excess primary production and accepted treatment protocols were followed properly. If past treatments had not been so effective, alum would not be a popular restoration strategy today. Nevertheless, there have been alum treatments that did not follow accepted application protocols, which led to inadequate distribution and buffering against pH drop in low alkalinity water, and poor flocking due to too much algae, too low a dose, or incomplete chemical mixing.

Early treatments in the 1970s-1980s in low-alkalinity lakes were under-dosed, even though a buffer was used (Cooke et al. 2005). Effectiveness was short-lived in a few cases, due either to under dosing or high external P sources, which minimized the importance of internal loading. Thus, treatment success and long-term effectiveness can be jeopardized by not following the accepted rules and methods of application (standards of practice), without knowing the importance of internal loading and timing relative to total P loading, and the appropriate dose. Treatments of two lakes in Washington State will be discussed with respect to application methods, doses used, and treatment effectiveness.

Importance of Internal Loading

The magnitude of internal loading and the associated fraction of the total load during summer are important quantities that will indicate the main source of P causing summer algal blooms, which are the usual cause for poor water quality. In shallow, polymictic lakes internal loading is directly available to the lighted water column and is often the largest contributor of P during the summer, relative to external sources. In Grand Lake St. Marys (GLSM), Ohio, a large (5,000 ha) and shallow (mean depth of 2 m) lake, internal loading accounted for 91% of the total summer P load in 2011 (Tetra Tech 2012).

In contrast, P from internal loading may not be available to epilimnetic algae in deeper, strongly stratified lakes, until fall turnover (Cooke et al. 2005). In these lakes, nutrient rich water is entrained into the epilimnion at turnover causing a fall bloom possibly composed of cyanobacteria. Sediments at shallower depths in the metalimnion and epilimnion can also be an internal source of P despite being oxic. Lake Oswego, OR, continued to have summer cyanobacteria blooms, even though hypolimnetic aeration had effectively reduced anoxic hypolimnetic P loading. An alum treatment to the littoral sediment in 2006 successfully curtailed the blooms (M. Rosenkranz, pers. comm).

Alum Distribution and Application Methods

Treatments to thermally stratified lakes were usually to the hypolimnion initially. Of the 12 dimictic lakes evaluated in Cooke et al. (2005), ten received hypolimnetic treatments only. That procedure is more time-consuming and costly, and possibly less effective than a surface application, given the likely importance of epilimnetic and metalimnetic sediments. With proper buffering, surface applications are usually standard procedure today, even in low-alkalinity lakes. Surface applications allow the floc to settle and remove P through the entire water column.

Wind-caused resuspension may redistribute the alum floc unevenly. Laboratory experiments have shown that alum floc resuspends five times easier than untreated sediment (Egemos et al. 2010). However, alum remained in the sediment in the center 40 percent of GLSM, despite windy conditions during treatment, as evidenced by sediment core data and water column Al concentrations during treatment (Tetra Tech 2013).

Wind may have contributed to uneven distribution of alum during treatment of Green Lake, Seattle, in 1991. Sediment cores in 1998 showed no Al marker from the treatment – the only lake of seven sampled without an obvious Al marker (Rydin et al. 2000), although wind speed at the time of application was less than 17 mph. In addition, the 1991 treatment was unevenly delivered to the lake surface with most of the alum added to the downwind portion of the lake. A subsequent treatment in 2004 was more carefully controlled under calm conditions. Sediment cores from littoral and deep sites after six months showed visible Al layers (Dugopolski et al. 2008). Given the possibility of wind-caused redistribution of the alum floc, as well as the safety of the alum applicator, lakes should be treated during calm periods.

Application equipment has progressed as alum treatments have become a widely accepted and effective management tool. Applications are now highly innovative and much more precise, safe, and effective. Current application equipment should be equipped with an on-board computer integrated with a global positioning system (GPS) and sonar. For best results, flow of the alum (and sodium aluminate, which is used to buffer pH changes in lakes with low alkalinity) should be monitored continuously with in-line sensors and adjusted based on application vessel speed, lake position, and water depth. For buffered treatments, the flows of alum and sodium aluminate are controlled independently to achieve the desired dose and ratio of alum to sodium aluminate. Chemical distribution systems, similar to that shown in Figure 1, are used most often for whole-lake buffered treatments that ensure complete mixing of alum and sodium aluminate in the lake. The figure illustrates how alum and buffer are to be delivered directly to the lake prior to coming in contact with each other, yet the delivery is in close proximity so that alum and buffer mix immediately upon entering the water. This ensures proper floc formation and pH buffering.

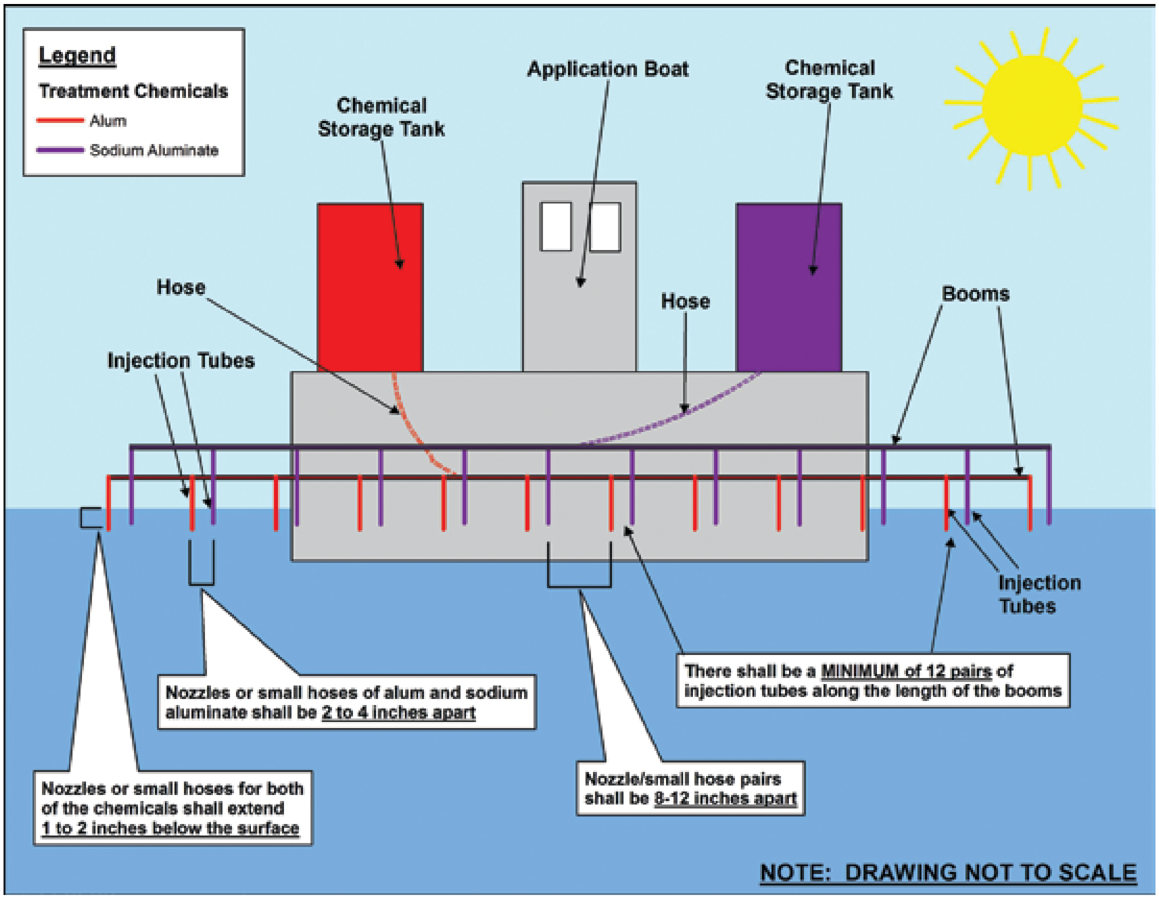

Figure 1. Schematic of an alum application barge with chemical distribution system.

Application and chemical distribution equipment should be constructed of material that meets corrosion resistant standards for alum and sodium aluminate (if applicable) and is rated for high temperatures. Such materials include stainless steel or heavy duty HDPE. If the proper materials are not used for chemical distribution and application, hose couplings and connectors, hoses, and tanks can fail leading to unnecessary leaks and spills of alum and/or sodium aluminate. Examples of alum application systems are shown in Figure 2, GLSM, Ohio 2011 and Figures 3 and 4, Long Lake, Kitsap County, Washington 2007. Incomplete chemical mixing can result in

Figure 2. Alum application Grand Lake St. Mary's, Ohio, June 2011.

Figure 3. Alum application barge used at Long Lake, Kitsap County, Washington, April 2007.

Figure 4. Alum application Long Lake, Kitsap County, Washington, April 2007.

pinpoint floc, which will not settle adequately, as well as, large swings in water column pH. Proper floc formation will maximize P inactivation while preventing adverse effects on aquatic organisms due to pH and micro-floc exposure.

Application of alum and sodium aluminate (if needed), should be guided by detailed technical specifications, which address all application elements in detail including lake morphometry, application vessels and equipment, chemical specifics, staging area and access, required time periods, safety precautions, and chemical distribution (dose, mixing rate, ratio of alum to sodium aluminate). Such specs are necessary so contractors are aware of lake specific conditions and requirements.

The treatment of Wapato Lake, Washington, in 2008 is an example of an effective P inactivation treatment that also had short-term adverse environmental impacts due to deviations from the technical specifications by the applicator. Toward the end of the treatment the applicator ran short of sodium aluminate and under-dosed the buffer by 17%. The result was an immediate pH shift from 7.8 to 4.2 with impacts to aquatic life. A week was needed after the treatment for the lake to recover to a pH of 7.2.

Al Dose Determination

Early treatment doses were determined by the magnitude of alkalinity. That is, the dose added was limited to prevent a decrease in pH below 6 (Cook et al. 2005). Dose is now calculated based on sediment P-fractions (mobile P and in some cases biogenic organic P) determined from cores (Rydin and Welch 1999). There is still some uncertainty regarding the depth of sediment mobile-P considered, because soluble reactive phosphorus (SRP) can diffuse upward from deeper sediments in response to the formation of the Al-P fraction from Al added to shallower sediments. Sediment depths used have varied from 4-10 cm (Rydin and Welch 1999; James and Barko 2003) and in rare occasions up to 20 cm.

Doses based on sediment mobile-P are often around 100 g Al/m^2, which is much higher (with adequate buffering) than earlier doses determined from alkalinity depletion. Average dose (±SD) to the 19 lake treatments evaluated by Cooke et al. was only 13 ± 9 g Al/m^2. Yet, only two of those treatments were considered unsuccessful, and some were highly successful with effectiveness lasting well over ten years. The average dose to 143 lakes treated in the world up to 2005, was 31 ± 24 g Al/m^2. If dose is too low and pH too high, an aluminum hydroxide [$Al(OH)_3$] floc may not form. That was the case with a low dose (2 g Al/m^2) to Lake Okaro, New Zealand, in which a cyanobacteria bloom was underway and pH > 8.5 (Quinn et al. 2004).

The ratio of Al added:Al-P to be formed (i.e., mobile P) used in estimating dose is recommended at about 100:1. That ratio may decline to 5:1-11:1 in the sediment after time as Al continues to sorb diffusing SRP from fresh sediment above and aged sediment below. An example of underdosing prior to using sediment P fractions is Lake Delevan, Wisconsin. That lake was dosed at 17.5-21.3 g/m^2 (depending on depth) in 1991 and the effect was short lived, whereas a dose determined from cores collected later was recommended at 190 g/m^2, based on sediment mobile P fractions, using 4 cm sediment depth and a ratio of 100:1 Al added:Al-P formed (Rydin and Welch 1999; Cooke et al. 2005).

Case Studies

Green Lake, Seattle, Washington
This important, 105-ha recreational lake in Seattle has a long history of eutrophication and on- going lake management. Lake quality was probably worsened when the water level was lowered 2.1 m in 1911 to drain adjoining wetlands. That lowering concentrated the internal P flux in the water column. The sediment P source amounted to 88% of total summer loading in 1981.

Various restoration methods have been used to improve Green Lake water quality and reduce nuisance algae blooms, including minimal dredging, dilution, copper sulfate treatments and, more recently, alum in 1991 and 2004. Buffered alum was added in 1991at a dose of 34 g Al/m², which was about half of the preferred dose due to cost limitation. Technical specifications were not followed during the treatment to reduce costs and the application was often performed under windy conditions in the summer when dense stands of milfoil were present. The probable poor alum distribution, physical and chemical (dissolved organic carbon [DOC]) interception of the floc by macrophytes, and lack of GPS guidance, as well as the low dose, likely compromised the effectiveness of the treatment. Nevertheless, the treatment was slightly effective: summer total P (TP) was reduced from 29 µg/L in 1989-1990 to 22 µg/L during 1992-2000 (Jacoby et al. 1994). The treatment was actually more effective than the data suggest, because there was dilution water added before the treatment, but not after. A more realistic pre-treatment TP concentration is 52 µg/L from 1981, without dilution. Water quality goals (summer TP < 25 µg/L and transparency > 2.5 m) were met for three to five years following that treatment.

Worsening water quality and the return of toxic cyanobacteria blooms required another alum treatment in 2004 (Figure 5). That dose was 98 g Al/m², determined by sediment P fractions (mobile P) plus water column TP. The treatment was carefully supervised and conducted in March before milfoil growth began to eliminate interception of the floc by macrophytes. This treatment was much more successful and long-lived; TP remained consistently at a summer average below 15 µg/L from 2004 through 2012, except for 2006 when it was 17.6 µg/L. Although summer TP has still remained low with 2013 and 2014 mean concentrations of 15.5 and 18.8 µg/L, respectively, fall peaks in chlorophyll (chl) have begun to appear with buoyant toxic cyanobacteria concentrating on beaches. Nevertheless, the markedly different results from the two alum treatments emphasize the need to properly determine the Al dose, supervise the application, and conduct the treatment at a time of year to avoid interference from macrophytes.

Lake Ketchum, Snohomish County, Washington. Lake Ketchum is a small (10.5 ha), relatively shallow (mean depth of 3.7 m) hypereutrophic lake located in Snohomish County, Washington. Lake Ketchum is the most eutrophic lake in the county and most likely western Washington, and has been plagued by toxic cyanobacteria blooms since 2000. Several improvements were made to the runoff from a former dairy farm at the south end of the watershed that reduced the P flowing into the lake; all cattle were removed, the import of animal waste stopped, and the land was converted to hay that is cut and removed each year. Although these improvements in the watershed led to a decline in TP in the epilimnion of the lake (long-term average of 270 µg/L, 1996-2013), the hypolimnetic TP concentrations continued to increase (long term average of 1,752 µg/L, 1996-2013) due to massive internal loading of P – a sediment release rate of 42 mg/m^2 per day. The lake's very high internal loading, a legacy of agricultural land use, contributed 73% of the lake's annual input of P in 2011 (98% of the total summer load) and hypolimnetic TP reached over 3 mg/L by late summer. These TP concentrations fueled nuisance

Figure 5. Alum application Green Lake, Seattle, Washington, March 2004.

algal production and toxic cyanobacteria with severe blooms occurring at fall turnover due to the entrainment of high P water from the hypolimnion.

A buffered alum treatment was recommended to inactivate sediment P and reduce internal loading by at least 85%. The treatment was 60% completed in May 2014 at a targeted dose of 84 g Al/m^2. The total volumetric dose for the treatment (sediment P inactivation + water column P stripping) was 28 mg Al/L. The treatment was stopped prior to completion because of multiple deviations from the technical specifications imposed by the contractor that resulted in several adverse environmental conditions. As illustrated in Figure 6, the treatment was still effective at reducing internal P loading (reducing May-October mean bottom TP from 1,427 µg/L in 2013 to 177 µg/L in 2014) but not to the desired concentration that would have prevented a toxic cyanobacteria bloom that occurred in November. Short-cutting standard procedures and not following technical specifications led to poor distribution and mixing of alum and sodium aluminate, resulting in inadequate floc formation and incomplete buffering throughout the water column. The remainder of the initial treatment is scheduled to be completed during spring 2015.

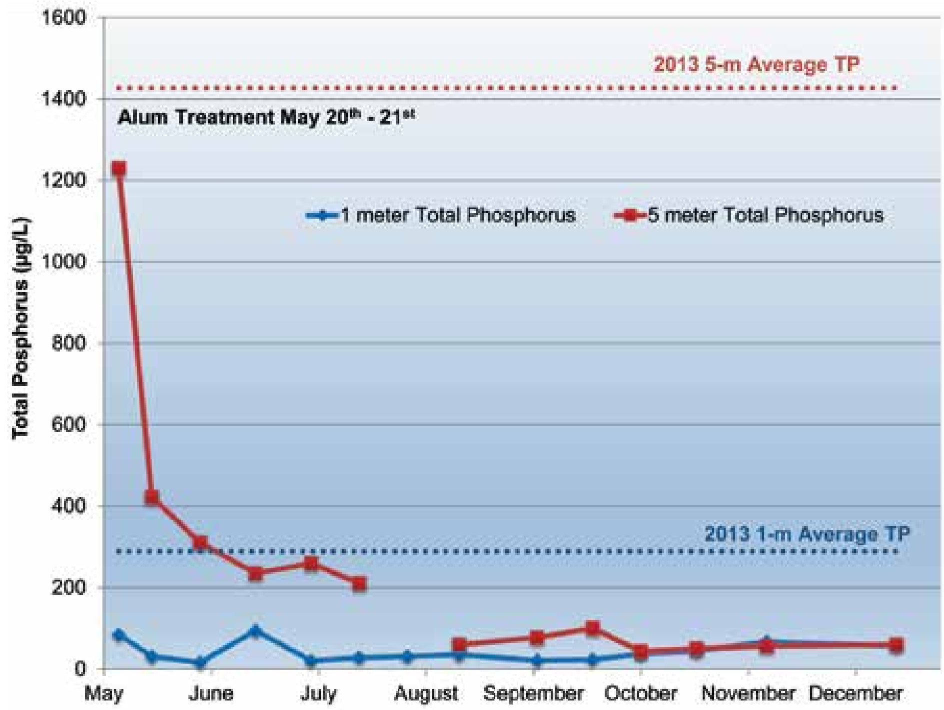

Figure 6. TP concentrations in Lake Ketchum following a large whole lake alum treatment in May 2014 (presented at NALMS International Symposium 2014; data courtesy of Snohomish County Surface Water Management).

Summary

The use of alum for nutrient inactivation has been used to control internal P loading for the past four decades. The level of success and effectiveness over these decades has been dependent upon treatments adhering to accepted methods of application, contractors following technical specifications, knowing the importance of internal loading, and adequate dosing.

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Shannon Brattebo is an environmental engineer for Tetra Tech, Inc. in Spokane, WA. Shannon's work has focused on lake and reservoir water quality, restoration, and management both in the Pacific Northwest and across the nation. Shannon has been a member of NALMS since 2001 and is a past board member of the Washington Lakes Protection Association.

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provided, and getting them something hot to eat or drink in the colder weather is important.

The Future

Our challenges of late include finding EWM in the middle of the lake in up to 17-foot depths. These plants are hard to find until they are very mature and tall enough to be seen with a bathyscope. They appear to be lankier and may grow slower than the EWM in shallower water, but all have fragments ready to launch at the top of each stem. It is quite possible that they have been there for many years sending off fragments that re-populate areas that we commonly harvest between the shoreline and up to 12-foot depths. This has added new territory that we have been having divers swim through to find them. We are hoping to purchase an underwater scooter to assist with this. We have had weather-related issues, such as tropical storms possibly combined with fertilizers and septic systems, causing an increase in nutrients in the lake, with EWM growth seeming to increase following these events.

The year 2014 was our 12th year hand-pulling invasive plants from Center Pond. In 2010 after eight years of effort these invasives were reduced to such low numbers that Aquatic Control Technology (ACT) reported that their management was no longer needed and the lake association could let their permit for chemical controls lapse. After a year without any surveys, the lake association retained Water Resource Services (WRS) as their lake management consultant, and they have reported that the hand-harvesting program is providing effective invasive control to date. WRS has provided detailed surveys; including finding the EWM growing in the middle of the lake using their underwater video camera, as well as getting us started using GPS technology and recommending other improvements we can make to the efficiency of our invasive plant control.

My role as director of this project takes a huge amount of my time, but it is time I enjoy and find very fulfilling. Prior to this I spent time at the beach relaxing and swimming. Instead I am often out in a canoe and get a quick swim before going to work. My job working in the evening into the night allows me a good part of the daytime to devote to the Center Pond Weed Project. Someone who is retired would be ideal for this, as would an arrangement for a number of people to split their lake into sections and manage the project for their area.

There are many other little pieces of the puzzle of controlling aquatic invasives that I have not addressed here: We developed foot-pulling where people remove EWM by the roots while standing in water as deep as up to their shoulders; hand-pulling any of these invasives from a canoe in shallow, mucky areas; and removing the seeds (turions) of curly-leaf, an annual, with a rake from a boat. It's important to be vigilant and always learning and trying new methods as you go. If you look and listen with all your senses to the plants and the lake ecosystem you can make sense of your observations and outsmart the invasives.

Mercedes Gallagher was on the board of directors and the Executive Director of Del-AWARE Unlimited in Bucks County, PA, in the 1980s and came to MA in 1990 to work as director of administration of the Kushi Institute in Becket. She joined the Becket Conservation Commission just months before the first diquat treatment of Center Pond was proposed and was the only member to vote against it. Her search for alternatives came to fruition when she learned about hand-pulling and two SCUBA divers offered their services in 2002. She works at the Red Lion Inn in Stockbridge, MA. You may reach Mercedes at: centerpondweedproject@yahoo.com.

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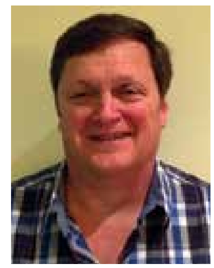
Gene Welch is professor emeritus, University of Washington, where he taught and researched water quality problems in lakes and streams for 29 years. Since 2000, he is senior limnologist with Tetra Tech, Inc., in Seattle. He has served as NALMS president (1993) and twice as board member.



Harry Gibbons has 40 years of experience leading the management and restoration programs for over 250 lakes/reservoir and 35 stream and river systems, and has developed and implemented several in-lake activities for techniques like phosphorus inactivation (alum), dredging, hypolimnetic aeration, aeration and circulation, AIS management, and integrated aquatic plant management. Harry has served NALMS twice on the board of directors and NALMS president in 2009. Harry received NALMS Secchi Disk Award in 2012.