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Freshwater Harmful Algal Bloom Mitigation Report: Hypolimnetic Oxygenation, Alum Treatment, and Phoslock®

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Purpose and Scope

This brief review of the scientific literature is a volunteer graduate student project for the California Cyanobacteria Harmful Algae Blooms Network, Mitigation Subcommittee. This brief review is not intended to be a comprehensive or exhaustive list of best migration practices, but rather a brief insight into selected mitigation techniques. These selected techniques were used to control internal cycling of phosphorus.

Introduction

Algae consist of large groups of autotrophic eukaryotes that lack many distinct characteristics found in terrestrial plants (Chapman et al. 1980). Algae play an important environmental role as algae is the base for aquatic food chains in addition to oxygen production and habitat. Additionally, it is a key source of medicine due to its antioxidant, anticancer, and antiviral properties (Pooja 2014). Unfortunately, algae can be a destructive force that pollutes water, creates financial burdens, and can be responsible for massive marine organism kill-offs (U.S. EPA 2013).

Algae can carry out photosynthesis to obtain functional amounts of carbon. They also need nutrients to thrive such as nitrogen and phosphorus. Unabated by humans, most algae species get their nitrogen from nitrates and nitrogenous compounds in water while some can fix it from air themselves (Stal 2015). In contrast, algae get their phosphorus exclusively from dissolved forms in the water. In the presence of excess soluble nutrients, algae may bloom uncontrollably. This starts a cascading affect where, as stated by Callisto et al. 2013, sunlight may never reach lower lake levels, killing off autotrophs and lowering the temperature of the water body. Microorganisms will then start to deplete oxygen supplies from the lake as they consume the organic matter. This leads to hypoxic then anoxic lake conditions known as eutrophication (Callisto et al., 2013). These large-scale Harmful Algal Blooms (HABs) have caused $2.2 billion in economic loss for freshwater systems (Dodds et al. 2009).

Furthermore, HABs, colloquially known as blue-green algae (cyanobacteria) blooms in fresh waters and red tides (diatoms) in marine waters can produce toxins and release them into the water. Gilroy et al. 2000 state that microcystins, produced from many species of cyanobacteria in waters, are potent hepatotoxins and probable tumor promotors (Gilroy et al. 2000). Domoic acid from red tides has been shown to bioaccumulate through bivalves (Perl et al. 1990) and cause serious nervous system damage (WDFW. Updated 2017). It is important to note that while HABs afflict both marine and freshwater systems, this report will solely investigate treatments for freshwater systems.

In 2014, Ohio governor John Kasich announced a state of emergency in the town of Toledo, Ohio due to a massive blue-green algae bloom that, according to the local media, left more than 400,000 people without drinking water (The Blade. 2014) for two days. Similar emergency advisories have occurred in Michigan and Florida; all 50 states are adversely affected by blooms (U.S. EPA. Updated 2017).

The threat to the ecosystem, human health, and economic livelihood has made it imperative to find solutions to these algal blooms. While nutrients are important for these algae to flourish, phosphorus is often the limiting nutrient. The nitrogen cycle involves nitrogen fixation of atmospheric nitrogen to ammonia, nitrification of ammonia to nitrite then nitrate, and eventually denitrification on nitrate to atmospheric nitrogen gas (Bernard 2010). As nitrogen gas is the major component of the atmosphere (79%), it is in constant exchange between land, water, and atmosphere. Phosphorus does not cycle with the atmosphere and thus tends to be in limited supply in aquatic ecosystems (Smith. 1984). However, phosphorus abundance has changed with the invention of phosphorus-based fertilizers, and lakes around the world are now being inundated by agricultural runoff (Sharpley et al. 2003).

Fortunately, sediments may act as phosphorus sinks. BostrÖm et al. 1988 state that in certain chemical conditions sediments can retain phosphorus, but in other chemical conditions sediments can release phosphorus into the water column. In oxygenated sediments, iron (III), or ferric iron, absorbs phosphorus and forms an insoluble ferric iron-phosphate complex. Nevertheless, when this iron gets reduced to ferrous iron, iron (II), in anaerobic conditions, then the iron-phosphorus complexes are dissolved and the subsequent release of phosphorus occurs, commonly called internal loading (BostrÖm et al. 1988).

Anaerobic conditions occur in lake bottom waters and sediments when lake water becomes thermally stratified. Lakes become thermally stratified when different depths of the water column contain different temperatures and densities of water (Lake Access.org). With seasonal temperature changes, lakes can internally mix once (monomictic), twice (dimictic), or several times (polymictic) throughout the year. Additionally, meromictic lakes can remain unmixed indefinitely. Water is unique in that it is densest at 4^{o}C (USGS) and decreasing temperatures will cause the formation of ice (USGA 2017). During spring in dimictic lakes, surface water temperature raises to 4^{o}C and ice melts, and this melt breaks the lake stratification. Eventually, over the summer, the warmer less dense water will remain as an upper layer (epilimnion) and the denser cooler water will fall to the hypolimnion reforming lake stratification. Cool fall weather will once again break the stratification, which will be re-established in winter upon ice-formation.

Thermal stratification protects the hypolimnion from mixing with upper layers, often even from wind mixing. In this way, the hypolimnion becomes devoid of atmospheric reaeration. Furthermore, higher trophic (i.e., eutrophic and hypereutrophic) lakes are too turbid for sub-thermocline photosynthesis (Buetel et al. 1999). Without an adequate source of oxygen, the hypolimnion may become hypoxic or even anoxic as respiring microorganisms degrade fallen biomass. This poses a serious threat to cold-water fish species that may need to move to warmer surface waters that contain more oxygen.

This paper investigates three ways to manage this internal loading of phosphorus during times of strong stratification: hypolimnetic oxygenation, alum treatment, and Phoslock®.

Hypolimnetic Oxygenation

Depending on restoration goals, hypolimnetic oxygenation can provide ample oxygen to the hypolimnion and can be configured to break or maintain thermal stratification. Oxygenated waters also help nitrification and subsequent denitrification (Bernhard et al. 2010), and will increase overall benthic diversity and density (Jónasson et al. 1984; Doke et al. 1997; Dinsmore et al. 1997).

There are several hypolimnetic oxygenation methods that maintain lake stratification (Debroux et al. 2012), such as fine-bubble line diffusers, side-stream pumps, and Speece Cones. These methods utilize the main benefits of using pure oxygen as compared to air (i.e., pure oxygen has higher solubility and higher transfer efficiency). Pure oxygen is roughly five times more soluble in water relative to air's solubility in water (Buetel et al. 1999). Oxygen also has a high transfer efficiency at up to 80% (Mobley et al. 2009). High solubility coupled with high transfer efficiency allows for better management of oxygen while employing smaller systems.

The Speece Cone, created by Richard Speece for the Tennessee Valley Authority (Speece 1971), has advantages over other methods of oxygenation because it avoids high maintenance costs, noise pollution, and aesthetic deterioration caused by other systems. The first *in situ* application for lake restoration came in 1992 in Newman Lake, WA. Moore et al. 2012 describe this installation as having a 5.5m high 2.8m diameter cone with the ability to deliver 1360 kg O_2/d at a depth of 8m. The true potential of this design comes from its ability to take in hypolimnetic water and oxygenate it and return it to the hypolimnion at similar density and temperature to surrounding water (Moore et al. 2012). This allows for efficient mixing of oxygenated water with the surrounding water. Restoration efforts have been successful in Newman Lake with decreased annual volume-weighted total phosphorus, peak observed total phytoplankton, peak observed cyanobacteria concentrations and improved transparency (Moore et al. 2009). Including Newman Lake, several other lakes have employed hypolimnetic oxygenation (HO) techniques to improve water quality; see HO tables.

In conclusion, there has been mixed success with hypolimnetic oxygenation. For example, the informative title of Gachter et al. 1998's paper "Ten Years of Artificial Mixing and Oxygenation: No Effect on the Internal Phosphorus Loading of Two Eutrophic Lakes." These lakes are Lake Sempach and Lake Baldegg, and the paper speaks to the necessity of thorough understanding of site-specific conditions to select an effective mitigation strategy. In contrast, as also can be seen on the HO tables, researchers at 8 of 13 lakes reported decreases in total phosphorus concentrations after HO treatment. Researchers at 3 of 13 lakes reported decreases in chlorophyll a concentrations. Additionally, at Newman Lake, both cyanobacteria and total phytoplankton concentrations decreased.

Alum Treatment

Nonetheless, the ability of iron to bind phosphorus depends on the sediment P-retention capacity that decreases with an increase of mobile P (Jensen et al. 1992). Furthermore, Gachter et al. 1998 argue that the lakes with high sulfate content can reduce ferric iron, which favors the precipitation of pyrite (FeS_2). In this way, iron is bound in pyrite form in the sediments and is not available upon return of aerobic conditions to oxidize ferrous iron into P-binding ferric iron, and so allows for continual internal P-cycling. (Gachter et al. 1998). Additionally, pH changes in calcareous lakes, such as Mono Lake, can dissolve calcite-P and can be a significant contributor of internal phosphorus loading (Penn et al. 1995).

Aluminum sulfate (informally known as alum) allows for the management of internal phosphorus loading by increasing the P-retention ability of sediments. Even when curtailing external phosphorus inputs with best management practices, a hypolimnion with low levels of oxygen can continue to load phosphorus into the lake. The Wisconsin Department of Natural Resources notes that upon contact with water, the alum forms an aluminum hydroxide flocculent. Similar to how ferric oxide binds to phosphorus, an insoluble aluminum phosphate compound is formed (WDNR 2003). One advantage to using alum is that unlike iron, a reducing environment will not solubilize the aluminum-bound phosphorus (Reitzel et al. 2005). Another advantage of alum use is the possibility of enduring effectiveness. Green Lake, Washington underwent an alum treatment in 2004 to deal with internal phosphorus loading. By studying the sediment cores 11 years later, it has been shown that mobile phosphorus levels have decreased by 60-80% (Welch et al. 2017). Seinman et al. 2017, however, had inconclusive results in which, after 11 years, Spring Lake, MI suggested internal loading had returned yet sediment release rates remained low.

Disputably the most important aspect of alum treatment is providing an appropriate dosing. In the presence of water, aluminum sulfate will produce aluminum hydroxide in addition to sulfuric acid. While aluminum hydroxide allows for the binding and ultimate sequestration of phosphorus, sulfuric acid can lower the lake's pH. Gensemer et al. 1999 reveal that aluminum hydroxyl species vary with surrounding pH where low pH will lead to the formation of toxic ionic aluminum (Al^{3+}) and high pH results in $Al(PH)_4^-$; thus ideal pH levels for $AL(OH)_3$ reside between 6-8 (Gensemer et al. 1999). Successful uses of alum have been most frequently noted in lakes with higher alkalinity (>75 mg $\cdot$ L^{-1} $CaCO_3$) that helps buffer the pH around ideal levels (Cooke et al. 1993). In acidic or low alkalinity lakes, buffers such as sodium aluminate or lime may be added to raise any decrease in pH (Gensemer et al. 1999).

Pilgrim et al. 2007 dosing strategy involved the determination of a dose response curve. They noted that a linear relationship formed between the P-release rate and the mobile-P content in sediment cores. This idea was built off of in 2017 in Cape Code Lakes when dose-response in conjunction with economic constraints lead to a dosing amount of 25 g/m^2 (Wagner et al. 2017).

A large area of concern with alum treatment is the possibility of aquatic toxicity. While aluminum hydroxide is insoluble and rather benign to aquatic life, acidic conditions can convert it to toxic Al^{3+}. Studies have shown this form of aluminum can replace calcium cations in the bodies of snails, bivalves, and crustaceans and can accumulate in gills of fish. Aluminum can also inhibit calcium, phosphorus, and iron metabolism in organisms and is most harmful to humans through its ability to replace magnesium and iron. The severest danger of aluminum to humans is its neurotoxicity (Barabasz et al. 2001). Similarity, basic pH levels have been shown to be toxic to juvenile rainbow trout when dissolved aluminum concentrations exceed 1.0 mg/L (Gunderson et al. 1994).

Lastly, alum treatments must coincide with external phosphorus controls. As stated by Steinman et al. 2017, continued external loading will render alum treatment unserviceable as binding sites will decrease (Steinman et al. 2017). Sorption capacity can also decrease due to increasing amounts of fresh sediment covering the Al-P layer (Lewandowski et al. 2003).

Nonetheless, alum treatments are extremely effective at removing phosphorus from the water column; see alum tables. Not stated in the alum tables was effectiveness pertaining to toxins. Researchers reported on Lake Ketchum's decrease in microcystin concentrations from a max of 551 µg/L in 2011 to negligible levels in 2016. Alum treatments have been used to restore lakes for over 55 years and have thus undergone extensive research (Cook et al. 1993). It is important for a comprehensive site investigation to occur before undergoing alum treatment to assure feasibility of treatment.

In conclusion, as can be seen on the alum tables, researchers at 23 of 24 lakes reported decreases in total phosphorus concentrations after alum treatment. Researchers at 18 lakes reported decreases in chlorophyll a concentrations and at 2 lakes reported increases; and steep decreases in toxins in Lake Ketchum.

Phoslock®

Alum treatments are effective at mitigating harmful algal blooms but are highly susceptible to changes in pH. Alternative treatment methods have been proposed that both are robust enough in having strong phosphorus binding potential and can withstand geochemical changes. Melnyk et al. 1974 reported that the rare earth metal lanthanum binds readily to phosphate and is effective over a wide range of pH changes (4.5-8.5). Once added to the water, lanthanum-bound phosphate, or rhabdophane, becomes highly insoluble with a K_{SP} of -25.76 (Liu et al 1997). Due to its resistance to release phosphorus under anoxic conditions (Ross et al. 2008), lanthanum is an effective HAB mitigation technique.

However, research has also shown that the release of highly oxidized La^{3+} is potentially toxic to aquatic organisms (Barry et al. 2000). Fortunately, the addition of a high-cation-exchange-capacity bentonite clay seals ionic lanthanum; this product is “lanthanum (La)-modified bentonite,” also known as Phoslock® (Haghseresht et al. 2009). A study by Lürling et al. 2010 revealed that only 0.001% of the lanthanum bound to the clay was released into the surrounding water column. Nonetheless, this small amount of released lanthanum is still toxic and while this study revealed no major detrimental effects on Daphnia (Lürling et al. 2010), Oosterhout et al. 2014 showed that marbled crayfish could bioaccumulate La from Phoslock ®. La concentration in abdominal muscles and gills had increased 23 and 122 fold; respectively. La concentration increases were also shown in ovaries and hepatopancreas. Phoslock® may also inhibit photoautotroph growth. Lake Rauwbraken utilized a treatment of alum and Phoslock ® known as “Flock and Lock”, causing a temporary disappearance of Daphnia for 3 months.

Phoslock® is applied to surface waters as a slurry and slowly falls toward lake bottoms where it settles into a thin layer of the sediment. While Phoslock® can scour phosphorus as it descends, turbidity is temporarily increased during application until the Phoslock® settles; a cause of worry in regard to the growth of phytoplankton species. This is a short-term adverse effect however, as Phoslock ® rapidly settles. Subsequent to settling, agitation of the Phoslock® sediment is unlikely (Oosterhout et al. 2011).

However, there is evidence that dissolved organic carbon can significantly impair Phoslock®’s potential to remove mobile phosphorus from the water column. A 2014 study by Lürling et al. revealed that humic substances both interfere with the binding potential of the La-modified clay as well as increase La concentrations in the water column (Lürling et al 2014). Consequently, in highly humic conditions, Phoslock ® should not be the only mode of action for phosphorus mitigation. Alkalinity will also alter the effectiveness of Phoslock®. Hard water lakes with $CaCO_3$ concentrations of 200 mg L^{1-} had 12% lower binding potential compared to theoretical values. This would make the suggested Phoslock®: P ratio of 100:1 insufficient to remove all mobile dissolved phosphorus from the water column (Reitzel et al. 2013).

With all this in mind, it should be stated that Phoslock® has undergone extensive *in vitro* and *in vivo* research and has been applied to over 200 environments (Copetti et al. 2016). Copetti et al. further go on to state that negligible human risk and very limited acute ecotoxicity reports make Phoslock® an appealing treatment for internal phosphorus loading; see Phoslock ® tables. It is important however to perform a comprehensive site review before treatment as high pH, alkalinity, and dissolved organic matter can significantly affect treatment.

In conclusion, as can be seen on the Phoslock® tables, researchers at 7 of 8 lakes reported decreases in aqueous phosphorus concentrations as a result of Phoslock® treatment. Laguna Niguel Lake also experienced a decrease in cyanobacteria cell count. Cane Parkway and Scanlon Creek Reservoir experienced decreases in algal cell count.

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Geographical Information on Lakes Incorporating Hypolimnetic Oxygenation

Lake	Location	Surface Area (km^2)	Mean Depth (m)	Maximum Depth (m)	Volume (10^6 m^3)	Lake Type	Main Issue
Lake Sempach	Switzerland	14.4	44	87			
Lake Baldegg	Switzerland	5.3	33	66	170	meromictic	Eutrophoication
Richard B. Russell Lake	Georgia	107.8	12	47	1300		Hypolimnetic Anoxia
Amisk Lake	Alberta, Canada	5	14.5	60	80	meromictic / dimictic	Eutrophication
Newman Lake	Washington	5.15	6	10	28	Dimictic	Algal Blooms
North Twin Lake	Washington	3.6	9.8	15.4	34.9	Dimictic	Fish Kills
Camanche Reservoir	California	29.6	17	31	510		Fish Kills & Hydrogen Sulfide Production
Lake Varese	Italy	14.5	10.7	26	153.65	monomictic	Eutrophication
Lake Hald	Denmark	3.4	13.1	31	45	Dimictic	Eutrophication
Lake Vedsted	Denmark	0.08	5	11.9	0.4	Dimictic	Eutrophication
Lake Viborg Nørresø	Denmark	1.2	7	12	8.6	Dimictic	Eutrophication

Geographical Information on Lakes Incorporating Hypolimnetic Oxygenation

Lake	Location	Surface Area (km^2)	Mean Depth (m)	Maximum Depth (m)	Volume (10^6 m^3)	Lake Type	Main Issue
Lake Torup	Denmark	0.02	3.92	9.5	0.8	Dimictic	Eutrophication
Lake Fure	Denmark	9.4	13.5	37.7	122.2	Dimictic	Eutrophication

Technical Information for Lakes Employing Hypolimnetic Oxygenation

Lake	System Type	Oxygenation Since	Operation Costs of Aeration	Oxygenation Rate (tons O2 D-1)	Number of Diffusers	Operation Costs of Oxygenation
Lake Sempach	Deep Oxygenation Injection Systems	1984	0.021 (USD kg^{-1} O_2)	3	8	
Lake Baldegg	Deep Oxygenation Injection Systems	1982	0.010 (USD kg^{-1} O_2)	3	6	0.311 (USD kg^{-1} O_2)
Richard B. Russell Lake	Deep Oxygenation Injection Systems	1985		200	2	$1.6 (M); $2.4 (M OM Y^{-1})
Amisk Lake	Deep Oxygenation Injection Systems	1990		0.5-1		
Newman Lake	Downflow bubble Contact System (Speece Cone)	1992		0.93	1	
North Twin Lake	Line Diffuser	2008				
Camanche Reservoir	Downflow bubble Contact System (Speece Cone)	1993		8		$1.8 (M); $108 (K OM/yr)
Lake Varese	Downflow bubble Contact System (Speece Cone)	2000				
Lake Hald	Line Diffuser	1985		0.27-0.82		
Lake Vedsted	Line Diffuser	1995		0.02		
Lake Viborg Nørresø	Line Diffuser	1996		0.03-0.38		

Technical Information for Lakes Employing Hypolimnetic Oxygenation

Lake	System Type	Oxygenation Since	Operation Costs of Aeration	Oxygenation Rate (tons O2 D-1)	Number of Diffusers	Operation Costs of Oxygenation
Lake Torup		2002		0.01-0.02		
Lake Fure	Deep Oxygenation Injection Systems	1982	0.010 (USD kg^{-1} O_2)	3	6	0.311 (USD kg^{-1} O_2)

Physico-Chemical Aspects of Lakes Employing Hypolimnetic Oxygenation

Lake (multiple Treatments)	Date Recorded		Maximum Bottom Total Phosphorus (mg P m^{-3})	Dissolved Phosphorus Concentration at Overturn (mg P m^3)	hypolimnetic O2 levels (mg O L^{-1})	Hypolimnetic DO Consumption	Phosphorus Release from Hypolimnion
Lake Sempach		**Pre-Oxygenated**					
		Oxygenated		160	1.5		
Lake Baldegg		**Pre-Oxygenated**					7 (tons)
		Oxygenated		520	1.5		2.0-2.8 (tons)
Richard B. Russell Lake	1983-1985	**Pre-Oxygenated**					
	1985-1986	**Oxygenated**			5		
Amisk Lake	1980-1987	**Pre-Oxygenated**	123				7.7 (mg m^{-2} D^{-1})
	1990-1993	**Oxygenated**	56				3 (mg m^{-2} D^{-1})
Newman Lake	(1974-1986)	**Pre-Oxygenated**	55			915 kg D^{-1}	
	1993	**Oxygenated**	21		5.5	1530 kg D^{-1}	
North Twin Lake	(2004-2007)	**Pre-Oxygenated**				3300 kg D^{-1}	
	(2009-2012)	**Oxygenated**					
Camanche Reservoir		**Pre-Oxygenated**				0.07 (mg L^{-1} D^{-1})	
	2004	**Oxygenated**			5-6	0.12 (mg L^{-1} D^{-1})	

Physico-Chemical Aspects of Lakes Employing Hypolimnetic Oxygenation

Lake (multiple Treatments)	Date Recorded		Maximum Bottom Total Phosphorus (mg P m^{-3})	Dissolved Phosphorus Concentration at Overturn (mg P m^3)	hypolimnetic O2 levels (mg O L^{-1})	Hypolimnetic DO Consumption	Phosphorus Release from Hypolimnion
Lake Varese	1990-1999	**Pre-Oxygenated**	180	130			12-11 (tons Y^{-1})
	(2001-2002)	**Oxygenated**	70	70			11-10 (tons Y^{-1})
Lake Hald (1985-2009; exclusing 1998 & 2006)	(1980-1984)	**Pre-Oxygenated**	800		0.5	˜200-300 (tons y^{-1}	0.1-0.7 (g m^{-2} Y^{-1})
	(1985-2009; exclusing 1998 & 2006)	**Oxygenated**	200		1.5-1.7		0.03-0.4 (g m^{-2} Y^{-1})
Lake Vedsted (1995-2007; exclusing 2002 & 2007)	(1990-1995)	**Pre-Oxygenated**	<400		2-3		
	(1995-2007; exclusing 2002 & 2007)	**Oxygenated**	150		2.2		
Lake Viborg Nørresø	(1990-1995)	**Pre-Oxygenated**	600		0.3		
	(1996-2007)	**Oxygenated**	400		1.2		
Lake Torup (2002-2007)	(1998-2001)	**Pre-Oxygenated**	<400		0.3	~7.1 (tons y^{-1})	
	(2002-2007)	**Oxygenated**	150		1.7		
Lake Fure (2003-2007)	(1998-2002)	**Pre-Oxygenated**	<400		<0.2	˜640-950 (tons y^{-1})	
	(2003-2007)	**Oxygenated**	150		>6		

Physico-Chemical Aspects of Lakes Employing Hypolimnetic Oxygenation

Lake (multiple Treatments)	Date Recorded		Maximum bottom Ammonium	Maximum Bottom Dissolved Organic Phosphorus	Maximum Bottom Methane (mg m^{-3})	Maximum Bottom Total Iron (mg Fe m^{-3})	Maximum Bottom Total Manganese (mg Mn m^{-3})	Maximum Bottom Hydrogen Sulfide (g H_2S m^{-3})
Lake Sempach		**Pre-Oxygenated**	90 (mg N m^{-3})		2.4	50	1000	0
		Oxygenated	50 (mg N m^{-3})		0	30	500	0
Lake Baldegg		**Pre-Oxygenated**	1500 (mg N m^{-3})		2.6	56	1000	1
		Oxygenated	50 (mg N m^{-3})		0.3	20	230	0
Richard B. Russell Lake	1983-1985	**Pre-Oxygenated**	100-800 (mg N m^{-3})	50-150 (mg P m^{-3})				
	1985-1986	**Oxygenated**	10-160 (mg N m^{-3})	10-30 (mg P m^{-3})				
Amisk Lake	1980-1987	**Pre-Oxygenated**	120 (mg N m^{-3})					
	1990-1993	**Oxygenated**	50 (mg N m^{-3})					
Newman Lake	(1974-1986)	**Pre-Oxygenated**						
	1993	**Oxygenated**						
North Twin Lake	(2004-2007)	**Pre-Oxygenated**				833	119	
	(2009-2012)	**Oxygenated**				243	32	
Camanche Reservoir		**Pre-Oxygenated**	0.1-1.7 (L^{-1})	0.2 (L^{-1})				
	2004	**Oxygenated**	<0.2 (L^{-1})	<.050 (L^{-1})				

Physico-Chemical Aspects of Lakes Employing Hypolimnetic Oxygenation

Lake (multiple Treatments)	Date Recorded		Maximum bottom Ammonium	Maximum Bottom Dissolved Organic Phosphorus	Maximum Bottom Methane ($mg\ m^{-3}$)	Maximum Bottom Total Iron ($mg\ Fe\ m^{-3}$)	Maximum Bottom Total Manganese ($mg\ Mn\ m^{-3}$)	Maximum Bottom Hydrogen Sulfide ($g\ H_2S\ m^{-3}$)
Lake Varese	1990-1999	**Pre-Oxygenated**						
	(2001-2002)	**Oxygenated**	55 (tons removed)					
Lake Hald (1985-2009; exclusing 1998 & 2006)	(1980-1984)	**Pre-Oxygenated**						
	(1985-2009; exclusing 1998 & 2006)	**Oxygenated**						
Lake Vedsted (1995-2007; exclusing 2002 & 2007)	(1990-1995)	**Pre-Oxygenated**						
	(1995-2007; exclusing 2002 & 2007)	**Oxygenated**						
Lake Viborg Nørresø	(1990-1995)	**Pre-Oxygenated**						
	(1996-2007)	**Oxygenated**						
Lake Torup (2002-2007)	(1998-2001)	**Pre-Oxygenated**						
	(2002-2007)	**Oxygenated**						
Lake Fure (2003-2007)	(1998-2002)	**Pre-Oxygenated**						
	(2003-2007)	**Oxygenated**						

Physico-Chemical Aspects of Lakes Employing Hypolimnetic Oxygenation

Lake (multiple Treatments)	Date Recorded		Turnover Sulfate (g SO_4 m^{-3})	Inorganic Nitrogen Mass Accumulation (tons Y^{-1})	Secchi Transparency (m)	Total Meythlmercury (µg MeHg L^{-1})
Lake Sempach		**Pre-Oxygenated**	11	28		
		Oxygenated	11	3		
Lake Baldegg		**Pre-Oxygenated**	17			
		Oxygenated	16			
Richard B. Russell Lake	1983-1985	**Pre-Oxygenated**				
	1985-1986	**Oxygenated**				
Amisk Lake	1980-1987	**Pre-Oxygenated**	11			
	1990-1993	**Oxygenated**				
Newman Lake	(1974-1986)	**Pre-Oxygenated**				
	1993	**Oxygenated**				
North Twin Lake	(2004-2007)	**Pre-Oxygenated**				0.77
	(2009-2012)	**Oxygenated**				0.58
Camanche Reservoir		**Pre-Oxygenated**				
	2004	**Oxygenated**				

Physico-Chemical Aspects of Lakes Employing Hypolimnetic Oxygenation

Lake (multiple Treatments)	Date Recorded		Turnover Sulfate (g SO_4 m^{-3})	Inorganic Nitrogen Mass Accumulation (tons Y^{-1})	Secchi Transparency (m)	Total Meythlmercury (µg MeHg L^{-1})
Lake Varese	1990-1999	**Pre-Oxygenated**			3.2	
	(2001-2002)	**Oxygenated**			4.9	
Lake Hald (1985-2009; exclusing 1998 & 2006)	(1980-1984)	**Pre-Oxygenated**			2-3	
	(1985-2009; exclusing 1998 & 2006)	**Oxygenated**			5	
Lake Vedsted (1995-2007; exclusing 2002 & 2007)	(1990-1995)	**Pre-Oxygenated**			1.7	
	(1995-2007; exclusing 2002 & 2007)	**Oxygenated**			2	
Lake Viborg Nørresø	(1990-1995)	**Pre-Oxygenated**				
	(1996-2007)	**Oxygenated**				
Lake Torup (2002-2007)	(1998-2001)	**Pre-Oxygenated**				
	(2002-2007)	**Oxygenated**			1.7	
Lake Fure (2003-2007)	(1998-2002)	**Pre-Oxygenated**				
	(2003-2007)	**Oxygenated**				

Physico-Chemical Aspects of Lakes Employing Hypolimnetic Oxygenation

Lake (multiple Treatments)	Date Recorded		Comments
Lake Sempach		Pre-Oxygenated	Monthly pre-oxygenation data
		Oxygenated	Oxygenated Data averaged over 'deepest sites'
Lake Baldegg		Pre-Oxygenated	Monthly pre-oxygenation data
		Oxygenated	Oxygenated Data averaged over 'deepest sites'
Richard B. Russell Lake	1983-1985	Pre-Oxygenated	Results were from an interim report only covering one year
	1985-1986	Oxygenated	
Amisk Lake	1980-1987	Pre-Oxygenated	Pre-oxygenation data was averaged over four sites
	1990-1993	Oxygenated	Project terminated in 1993
Newman Lake	(1974-1986)	Pre-Oxygenated	In congruence with alum treatments
	1993	Oxygenated	Data was collected from three sites
North Twin Lake	(2004-2007)	Pre-Oxygenated	Study was mostly concerned with ecological effects of HO
	(2009-2012)	Oxygenated	
Camanche Reservoir		Pre-Oxygenated	
	2004	Oxygenated	

Physico-Chemical Aspects of Lakes Employing Hypolimnetic Oxygenation

Lake (multiple Treatments)	Date Recorded		Comments
Lake Varese	1990-1999	**Pre-Oxygenated**	Monthly monitoring at three stations
	(2001-2002)	**Oxygenated**	
Lake Hald (1985-2009; exclusing 1998 & 2006)	(1980-1984)	**Pre-Oxygenated**	Oxygenation benefits may have come as the result of strong external controls
	(1985-2009; exclusing 1998 & 2006)	**Oxygenated**	
Lake Vedsted (1995-2007; exclusing 2002 & 2007)	(1990-1995)	**Pre-Oxygenated**	
	(1995-2007; exclusing 2002 & 2007)	**Oxygenated**	
Lake Viborg Nørresø	(1990-1995)	**Pre-Oxygenated**	
	(1996-2007)	**Oxygenated**	
Lake Torup (2002-2007)	(1998-2001)	**Pre-Oxygenated**	
	(2002-2007)	**Oxygenated**	
Lake Fure (2003-2007)	(1998-2002)	**Pre-Oxygenated**	
	(2003-2007)	**Oxygenated**	

Biological Aspects of Lakes Employing Hypolimnetic Oxygenation

Lake		Suitable Salmonid Habitat	Average Clorophyll (mg Chl m-3)	Observed Cyanobacteria Concentration (10^6 cm^3 m^{-3})	Observed Total Phytoplanton Concentration (10^6 cm^3 m^{-3})	Biological Observance
Lake Sempach	**Pre-Oxygenated**					
	Oxygenated					
Lake Baldegg	**Pre-Oxygenated**					
	Oxygenated					
Richard B. Russell Lake	**Pre-Oxygenated**					
	Oxygenated					
Amisk Lake	**Pre-Oxygenated**		16.68			
	Oxygenated		7.50			
Newman Lake	**Pre-Oxygenated**			160	175	
	Oxygenated			1.1	15.7	
North Twin Lake	**Pre-Oxygenated**	0-58%				**Trout below 6m** 27-28%
	Oxygenated	1				**Trout below 6m** 35%
Camanche Reservoir	**Pre-Oxygenated**					
	Oxygenated					
Lake Varese	**Pre-Oxygenated**		40			
	Oxygenated		17			
Lake Hald	**Pre-Oxygenated**		62			
	Oxygenated		13			

Biological Aspects of Lakes Employing Hypolimnetic Oxygenation

Lake		Suitable Salmonid Habitat	Average Clorophyll (mg Chl m-3)	Observed Cyanobacteria Concentration (10^6 cm^3 m^{-3})	Observed Total Phytoplanton Concentration (10^6 cm^3 m^{-3})	Biological Observance
Lake Vedsted	**Pre-Oxygenated**					
	Oxygenated					
Lake Viborg Nørresø	**Pre-Oxygenated**					
	Oxygenated					
Lake Torup	**Pre-Oxygenated**					
	Oxygenated					
Lake Fure	**Pre-Oxygenated**					
	Oxygenated					

References for Lakes Employing Hypolimnetic Oxygenation

Lake	References
Lake Sempach	Gächter et al. 1998
Lake Baldegg	Beutel et al. 1999; Gächter et al. 1998
Richard B. Russell Lake	Beutel et al. 1999
Amisk Lake	Beutel et al. 1999; Tom et al. 1997
Newman Lake	Beutel et al. 1999; Moore et al. 2012 & 2015
North Twin Lake	Dent et al. 2014
Camanche Reservoir	Beutel et al. 1999
Lake Varese	Premazzi et al. 2005
Lake Hald	Liboriussen et al. 2009
Lake Vedsted	Liboriussen et al. 2009
Lake Viborg Nørresø	Liboriussen et al. 2009
Lake Torup	Liboriussen et al. 2009
Lake Fure	Liboriussen et al. 2009

Geographical Information on Lakes Employing Alum Treatment

Lake	Location	Year of Treatment	Area (ha)	Volume (10^6 m^3)	Mean Depth (m)	Max Depth (m)	Lake Type
Lake Sønderby	Denmark	2001	8		2.8	5.7	Polymictic
Lake Nordborg	Denmark	2006	55		5	8.5	
Lake Ketchum	Seattle	2014	10.5			6.7	
Lake Flaten	Sweden	2000	63		7.4	13.6	Dimictic
Långsjön	Sweden	2006	29		2.2	3.3	Polymictic
Lake Hamblin	Cape Cod	1995 2015	46		8.3	18.8	
Lake Ashumet	Cape Cod	2001 2010	82		7	20	
Lake Long	Cape Cod	2007	296		8.8	21.2	
Lake Mystic	Cape Cod	2010	59		4.6	14.3	
Lake Lovers	Cape Cod	2010	15		4.6	10	
Lake Stillwater	Cape Cod	2010	7.5		6.8	13.9	
Lake Herring	Cape Cod	2012	17.7		6.2	10.9	
Lake Great	Cape Cod	2013	44.7		3.6	11	
Lake Lovell's	Cape Cod	2014	22		5.7	11.4	

Geographical Information on Lakes Employing Alum Treatment

Lake	Location	Year of Treatment	Area (ha)	Volume (10^6 m^3)	Mean Depth (m)	Max Depth (m)	Lake Type
Lake Cliff	Cape Cod	2016	83		8.6	26.7	
Pinto Lake	California	2016	48				
Green Lake	Washinton	1991	105	4.25	3.9	8.2	Polymictic
Green Lake	Washinton	2004	105	4.25	3.9	8.2	Polymictic
Lake Morey	Vermont	1986	220		8.4	13	Dimictic
Calhound Lake	Minnesota	2001	180		10.6	27.4	Dimictic
Isles Lake	Minnesota	1996	44.2		2.7	9.4	Polymictic
Cedar Lake	Minnesota	1996	69.8		6.1	15.5	Dimictic (But has been known to only partially mix)
Spring Lake	Michigan	2005	525		6	13	
Newman Lake	Washington	1997	515	28	6	10	Dimictic

Treatment Aspects of Lakes Employing Alum Treatment

Lake (Incorporating only Alum)	Lake (Incorporating multiple treatments)	Year of Treatment	Needed Molar Ratio of Al:P	Alum Applied	Sodium Aluminate	Corresponding Aluminum Dose	% of Lake Treated	Dosing Duration
Lake Sønderby		2001	4:1	26 (m^3)		31 (g Al per m^2)		
Lake Nordborg		2006	8:1			52 (g Al per m^2)		
Lake Ketchum		2014	20:1	77.16 (m^3)	38.51 (m^3)	28 (mg Al per L^{-1})		Two doses in MAY 2014 Two doses in March 2015
Lake Flaten		2000				61 (g Al per m^2)		
Långsjön		2006				75 (g Al per m^2)		
Lake Hamblin		1995 2015				45 (g Al per m^2)	69.6 58.7	
Lake Ashumet		2001 2010				43 (g Al per m^2)	13.8 27.8	
Lake Long		2007				10-30 (g Al per m^2)	50	
Lake Mystic		2010				30-50 (g Al per m^2)	39.3	
Lake Lovers		2010				100 (g Al per m^2)	66.7	
Lake Stillwater		2010				100 (g Al per m^2)	66.7	

Treatment Aspects of Lakes Employing Alum Treatment

Lake (Incorporating only Alum)	Lake (Incorporating multiple treatments)	Year of Treatment	Needed Molar Ratio of Al:P	Alum Applied	Sodium Aluminate	Corresponding Aluminum Dose	% of Lake Treated	Dosing Duration
Lake Herring		2012				75 (g Al per m^2)	45.2	
Lake Great		2013				25 (g Al per m^2)	25.1	
Lake Lovell's		2014				50 (g Al per m^2)	63.6	
Lake Cliff		2016				75 (g Al per m^2)	37.3	
Pinto Lake		2016						
Green Lake		1991		181 (tons)	76.5 (tons)	8.6 (mg Al per L^{-1})		
Green Lake		2004		454 (tons)	261 (tons)	23.9 (mg Al per L^{-1})		Dosed over 15 days
Lake Morey		1986				43 (g Al per m^2)		
Calhound Lake		2001						
Isles Lake		1996						
Cedar Lake		1996						

Treatment Aspects of Lakes Employing Alum Treatment

Lake (Incorporating only Alum)	Lake (Incorporating multiple treatments)	Year of Treatment	Needed Molar Ratio of Al:P	Alum Applied	Sodium Aluminate	Corresponding Aluminum Dose	% of Lake Treated	Dosing Duration
Spring Lake		2005				80 (g Al per m^2)		
	Newman Lake	1997		214.3 (tons)				

Treatment Aspects of Lakes Employing Alum Treatment

Lake (Incorporating only Alum)	Lake (Incorporating multiple treatments)	Year of Treatment	Expected Time Frame of Effectivness	Comments
Lake Sønderby		2001		
Lake Nordborg		2006		
Lake Ketchum		2014		Annual spring alum treatments were planned for subsequent years.
Lake Flaten		2000		Study investigated new alum injection method
Långsjön		2006		
Lake Hamblin		1995 2015		
Lake Ashumet		2001 2010		
Lake Long		2007		
Lake Mystic		2010		
Lake Lovers		2010		
Lake Stillwater		2010		

Treatment Aspects of Lakes Employing Alum Treatment

Lake (Incorporating only Alum)	Lake (Incorporating multiple treatments)	Year of Treatment	Expected Time Frame of Effectivness	Comments
Lake Herring		2012		
Lake Great		2013		
Lake Lovell's		2014		
Lake Cliff		2016		
Pinto Lake		2016		
Green Lake		1991		
Green Lake		2004		
Lake Morey		1986		
Calhound Lake		2001		
Isles Lake		1996		
Cedar Lake		1996		

Treatment Aspects of Lakes Employing Alum Treatment

Lake (Incorporating only Alum)	Lake (Incorporating multiple treatments)	Year of Treatment	Expected Time Frame of Effectivness	Comments
Spring Lake		2005		
	Newman Lake	1997		Added as microfloc to the oxygenation system

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		Total Phosphorus (mg P L^{-1})	Dissolved Inorganic Phosphorus (mg P L^{-1})	Chlorophyll a (µg Chl a L^{-1})	Secchi Depth (m)	pH	Alkalinity (mEq L^{-1})
Lake Sønderby	2000	**Pre-treatment**	1.28	1.16	51	1.04	8.35	3.33
	2003	**Post-treatment**	0.13	0.05	44	1.88	8.39	2.74
Lake Nordborg	2006	**Pre-treatment**	0.238	0.663	26.5	2.3	8.2	3.5
	2009	**Post-treatment**	0.065	0.053	36.4	1.5	-	3.4
Lake Ketchum	2013 (at 5m)	**Pre-treatment**	1.427	1.235	56	1.7		
	2016 (at 5m)	**Post-treatment**	0.002	0.002	5	3.5		
Lake Flaten	1995-1999	**Pre-treatment**	0.0233		8.1	3.8	8.5	
	2001-2015	**Post-treatment**	0.0086		2.9	6.4	8.3	
Långsjön	1995-2005	**Pre-treatment**	0.115		78.6	0.8	8.9	
	2007-2015	**Post-treatment**	0.037		21.5	8.9	8.1	

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		Total Phosphorus (mg P L^{-1})	Dissolved Inorganic Phosphorus (mg P L^{-1})	Chlorophyll a (µg Chl a L^{-1})	Secchi Depth (m)	pH	Alkalinity (mEq L^{-1})
Lake Hamblin (1997 & 2015)	1992-1995 2012-2015	**Pre-treatment**	**Bottom** 0.454 0.310		21.3 37.9	1.8 1.9		
	1995-1997 2015-2017	**Post-treatment**	**Bottom** 0.046 0.013		2.0 1.2	5.6 7.8		
Lake Ashumet (2001 &2010)	1998-2001 2007-2010	**Pre-treatment**	**Bottom** 0.290 0.300		6.4 5.7	2.8 2.9		
	2001-2003 2010-2013	**Post-treatment**	**Bottom** 0.100 0.060		4.1 3.2	3.5 3.8		

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		Total Phosphorus (mg P L^{-1})	Dissolved Inorganic Phosphorus (mg P L^{-1})	Chlorophyll a (µg Chl a L^{-1})	Secchi Depth (m)	pH	Alkalinity (mEq L^{-1})
Lake Long	2004-2007	**Pre-treatment**	**Bottom** 0.163		12.6	2.8		
	2007-2009	**Post-treatment**	**Bottom** 0.062		5.5	5.4		
Lake Mystic	2007-2010	**Pre-treatment**	**Bottom** 0.555		19.7	1.2		
	2010-2012	**Post-treatment**	**Bottom** 0.065		3.5	3.9		

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		Total Phosphorus (mg P L^{-1})	Dissolved Inorganic Phosphorus (mg P L^{-1})	Chlorophyll a (µg Chl a L^{-1})	Secchi Depth (m)	pH	Alkalinity (mEq L^{-1})
Lake Lovers	2007-2010	**Pre-treatment**	**Bottom** 0.116		32.2	1		
	2010-2012	**Post-treatment**	**Bottom** 0.024		2.4	3		
Lake Stillwater	2007-2010	**Pre-treatment**	**Bottom** 0.290		21.6	1.3		
	2010-2012	**Post-treatment**	**Bottom** 0.038		1.8	3.3		

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		Total Phosphorus (mg P L^{-1})	Dissolved Inorganic Phosphorus (mg P L^{-1})	Chlorophyll a (µg Chl a L^{-1})	Secchi Depth (m)	pH	Alkalinity (mEq L^{-1})
Lake Herring	2009-2012	**Pre-treatment**	**Bottom** 0.357		19	0.5		
	2012-2014	**Post-treatment**	**Bottom** 0.021		2.9	4.4		
Lake Great	2010-2013	**Pre-treatment**	**Bottom** 0.057		8.4	2.3		
	2013-2015	**Post-treatment**	**Bottom** 0.032		6.5	2.5		

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		Total Phosphorus (mg P L^{-1})	Dissolved Inorganic Phosphorus (mg P L^{-1})	Chlorophyll a (µg Chl a L^{-1})	Secchi Depth (m)	pH	Alkalinity (mEq L^{-1})
Lake Lovell's	2011-2014	**Pre-treatment**	**Bottom** 0.167		14.3	2		
	2014-2016	**Post-treatment**	**Bottom** 0.035		2.3	4.2		
Lake Cliff	2013-2016	**Pre-treatment**	**Bottom** 0.087		12.6	2		
	2016-	**Post-treatment**	**Bottom** 0.012		1.8	5.7		
Pinto Lake	2016	**Pre-treatment**	**Bottom** 0.73	**Bottom** 0.47				
	2017	**Post-treatment**	**Bottom** 0.07	**Bottom** 0.02				
Green Lake	1981	**Pre-treatment**	0.04			1.9		

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		Total Phosphorus (mg P L^{-1})	Dissolved Inorganic Phosphorus (mg P L^{-1})	Chlorophyll a (µg Chl a L^{-1})	Secchi Depth (m)	pH	Alkalinity (mEq L^{-1})
	1991-1993	**Post-treatment**	0.014 - 0.035			6.1		
Green Lake		**Pre-treatment**	0.016			2.5		
	2004	**Post-treatment**	0.005 - 0.014			5.4-2.9		
Lake Morey	(1975-1985)	**Pre-treatment**	**Bottom** 0.137		0.013	4		
	(1986-1998)	**Post-treatment**	**Bottom** 0.023		0.005	7.2		
Calhound Lake	(1971-2000)	**Pre-treatment**	**Eplimnetic** 0.036		12.2	2.7		
	(2002-2005)	**Post-treatment**	**Eplimnetic** 0.015		3.7	4.7		
Isles Lake	(1989-1996)	**Pre-treatment**	**Eplimnetic** 0.066		35.3	1.1		
	(2002-2005)	**Post-treatment**	**Eplimnetic** 0.046		28.3	1.6		
Cedar Lake	(1944-1996)	**Pre-treatment**	**Eplimnetic** 0.043		14.9	1.8		
	(2002-2005)	**Post-treatment**	**Eplimnetic** 0.024		7.3	2.8		

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		Total Phosphorus (mg P L^{-1})	Dissolved Inorganic Phosphorus (mg P L^{-1})	Chlorophyll a (µg Chl a L^{-1})	Secchi Depth (m)	pH	Alkalinity (mEq L^{-1})
Spring Lake	(2003-2004)	**Pre-treatment**	**Bottom** 0.07	**Bottom** 0.03	13.6 **Bottom** 4.55	1	8.5 **Bottom** 8.1	
	(2005)	**Post-treatment**	**Bottom** 0.035	**Bottom** <.005	**Surface Water** 17.3 **Bottom** 14.4	0.55	**Surface Water** 8.4 **Bottom** 7.8	
Newman Lake	(1974-1986)	**Pre-treatment**				**average decrease after turnonver** 0.7		15.3-16.2 mg L^{-1} CaCO3
	(1997-2007)	**Post-treatment**	0.018			**average increase after turnover** 0.7		10.3-12 mg L^{-1} CaCO3

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		TN:TP (molar)	Total Nitrogen (mg N L^{-1})	Nitrate (mg NO_3^- L^{-1})	Ammonium (mg NH_4^+ L^{-1})	Oxygen (mg O L^{-1})	Comments
Lake Sønderby	2000	**Pre-treatment**	3.12					
	2003	**Post-treatment**	22.2					
Lake Nordborg	2006	**Pre-treatment**	7-18	1.2	0.2	0.22	3.5	Data averaged over 5 sampling sites
	2009	**Post-treatment**	24-123	1.1	0.2	0.03	6.6	
Lake Ketchum	2013 (at 5m)	**Pre-treatment**	6.9	4.62				Average of monthly data
	2016 (at 5m)	**Post-treatment**	35.6	0.752				
Lake Flaten	1995-1999	**Pre-treatment**						Averaged data
	2001-2015	**Post-treatment**						
Långsjön	1995-2005	**Pre-treatment**						Averaged data
	2007-2015	**Post-treatment**						

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		TN:TP (molar)	Total Nitrogen (mg N L^{-1})	Nitrate (mg NO_3^- L^{-1})	Ammonium (mg NH_4^+ L^{-1})	Oxygen (mg O L^{-1})	Comments
Lake Hamblin (1997 & 2015)	1992-1995 2012-2015	**Pre-treatment**						Pre-treamtent data was averaged over three years
	1995-1997 2015-2017	**Post-treatment**						Post-treatment data averaged over monthly data for two years
Lake Ashumet (2001 &2010)	1998-2001 2007-2010	**Pre-treatment**						Pre-treamtent data was averaged over three years
	2001-2003 2010-2013	**Post-treatment**						Post-treatment monthly data averaged over two years

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		TN:TP (molar)	Total Nitrogen (mg N L^{-1})	Nitrate (mg NO_3^- L^{-1})	Ammonium (mg NH_4^+ L^{-1})	Oxygen (mg O L^{-1})	Comments
Lake Long	2004-2007	**Pre-treatment**						Pre-treamtent data was averaged over three years
	2007-2009	**Post-treatment**						Post-treatment monthly data averaged over two years
Lake Mystic	2007-2010	**Pre-treatment**						Pre-treamtent data was averaged over three years
	2010-2012	**Post-treatment**						Post-treatment monthly data averaged over two years

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		TN:TP (molar)	Total Nitrogen (mg N L^{-1})	Nitrate (mg NO_3^- L^{-1})	Ammonium (mg NH_4^+ L^{-1})	Oxygen (mg O L^{-1})	Comments
Lake Lovers	2007-2010	**Pre-treatment**						Pre-treamtent data was averaged over three years
	2010-2012	**Post-treatment**						Post-treatment monthly data averaged over two years
Lake Stillwater	2007-2010	**Pre-treatment**						Pre-treamtent data was averaged over three years
	2010-2012	**Post-treatment**						Post-treatment monthly data averaged over two years

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		TN:TP (molar)	Total Nitrogen (mg N L^{-1})	Nitrate (mg NO_3^- L^{-1})	Ammonium (mg NH_4^+ L^{-1})	Oxygen (mg O L^{-1})	Comments
Lake Herring	2009-2012	**Pre-treatment**						Pre-treamtent data was averaged over three years
	2012-2014	**Post-treatment**						Post-treatment monthly data averaged over two years
Lake Great	2010-2013	**Pre-treatment**						Pre-treamtent data was averaged over three years
	2013-2015	**Post-treatment**						Post-treatment monthly data averaged over two years

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		TN:TP (molar)	Total Nitrogen (mg N L^{-1})	Nitrate (mg NO_3^- L^{-1})	Ammonium (mg NH_4^+ L^{-1})	Oxygen (mg O L^{-1})	Comments
Lake Lovell's	2011-2014	**Pre-treatment**						Pre-treamtent data was averaged over three years
	2014-2016	**Post-treatment**						Post-treatment monthly data averaged over two years
Lake Cliff	2013-2016	**Pre-treatment**						Pre-treamtent data was averaged over three years
	2016-	**Post-treatment**						Post-treatment monthly data averaged over two years
Pinto Lake	2016	**Pre-treatment**			**Bottom** 0.32	**Bottom** 1.19		These values are averaged from four monitoring sites
	2017	**Post-treatment**			**Bottom** 0.02	**Bottom** 0.21		
Green Lake	1981	**Pre-treatment**						Samples were collected weekly, bi-weekly, and monthly and averaged

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		TN:TP (molar)	Total Nitrogen (mg N L^{-1})	Nitrate (mg NO_3^- L^{-1})	Ammonium (mg NH_4^+ L^{-1})	Oxygen (mg O L^{-1})	Comments
	1991-1993	**Post-treatment**						and averaged
Green Lake		**Pre-treatment**						Short-term study; Post-treatment data averaged over monthly data collected for 6 months.
	2004	**Post-treatment**						
Lake Morey	(1975-1985)	**Pre-treatment**					**Bottom** 1.9	Data averaged over late summer data
	(1986-1998)	**Post-treatment**					**Bottom** 5.7	
Calhound Lake	(1971-2000)	**Pre-treatment**						Data averaged over semi-monthly, monthly, and sporadically collected data
	(2002-2005)	**Post-treatment**						
Isles Lake	(1989-1996)	**Pre-treatment**						Data averaged over semi-monthly, monthly, and sporadically collected data
	(2002-2005)	**Post-treatment**						
Cedar Lake	(1944-1996)	**Pre-treatment**						Data averaged over semi-monthly, monthly, and sporadically collected data
	(2002-2005)	**Post-treatment**						

Physico-Chemical Aspects of Lakes Employing Alum Treatment

Lake (multiple treatments)	Date Recorded		TN:TP (molar)	Total Nitrogen (mg N L^{-1})	Nitrate (mg NO_3^- L^{-1})	Ammonium (mg NH_4^+ L^{-1})	Oxygen (mg O L^{-1})	Comments
Spring Lake	(2003-2004)	**Pre-treatment**					8 **Bottom** 3.08	Short-term study; Post-Treatment averaged over monthly data collected for 8 months.
	(2005)	**Post-treatment**					**Surface Water** 8.9 **Bottom** 3.63	
Newman Lake	(1974-1986)	**Pre-treatment**						Secchi depths were reported as increases or decreases in water transparency after turnover events. The pre-treatment data is an average of 16 turnover events while the post treatment data is the average of 21 events
	(1997-2007)	**Post-treatment**						

References for Lakes Employing Alum Treatment

Lake	Reference
Lake Sønderby	Reitzel et al. 2005
Lake Nordborg	Egemose et al. 2010; Jensen et al. 2015
Lake Ketchum	Brattebo et al. 2017
Lake Flaten	Schütz et al. 2017
Långsjön	Schütz et al. 2017
Lake Hamblin (1997 & 2015)	Wagner et al. 2017
Lake Ashumet (2001 &2010)	Wagner et al. 2017
Lake Long	Wagner et al. 2017
Lake Mystic	Wagner et al. 2017
Lake Lovers	Wagner et al. 2017
Lake Stillwater	Wagner et al. 2017
Lake Herring	Wagner et al. 2017
Lake Great	Wagner et al. 2017
Lake Lovell's	Wagner et al. 2017
Lake Cliff	Wagner et al. 2017
Pinto Lake	City of Watsonville Unpublished 2017
Green Lake	Jacoby et al. 1994
Green Lake	Jacoby et al. 1994
Lake Morey	Smelzer et al. 1999
Calhound Lake	Huser et al. 2011
Isles Lake	Huser et al. 2011
Cedar Lake	Huser et al. 2011
Spring Lake	Steinman et al. 2008
Newman Lake	Moore et al. 2009

Geographical Information on Lakes Employing Phoslock® Treatment

Lake	Location	Year of Treatment	Area (ha)	Volume ($10m^3$)	Mean Depth (m)	Max Depth (m)	Lake Type
Lake Het Groene Eiland	The Netherlands	2008	5	130	2.5	4.5	
Swan Lake	Ontario, Canada	2013	5.5	102	1.86	4.4	polymictic
Laguna Niguel Lake	California	2012	12.42		3.66	9.45	
Lake Rauwbraken	The Netherlands	2008	4			15	
Cane Parkway	Ontario, Canada	2008	0.43		2		
Scanlon Creek Reservoir	Ontario, Canada	2008	3.4		7		
Loch Flemington	Scotland	2010	15		0.75	2.9	
Bärensee	Germany	2007	6	156	2.63	3.8	polymictic

Geographical Information on Lakes Employing Phoslock® Treatment

Lake	Comments
Lake Het Groene Eiland	Used temporary dikes to separate this lake from surrounding 220-ha water body
Swan Lake	Susceptible to occasional stratification
Laguna Niguel Lake	
Lake Rauwbraken	
Cane Parkway	Urban stormwater management pond
Scanlon Creek Reservoir	
Loch Flemington	
Bärensee	

Treatment Aspects of Lakes Employing Phoslock® Treatment

Lake (Employing only Phoslock®)	Lake (Incorporating multiple treatments)	Year of Treatment	Phoslock® Applied (Metric Tons)	Additional Additives	Dosing Duration
	Lake Het Groene Eiland	2008	**2008** 11 **2009** 3.1		2008-2009
Swan Lake		2013	25.3		
Laguna Niguel Lake		2013	51.34		Over two days in April 2013
Lake Rauwbraken		2008	18	2 MT Alum 75 kg $Ca(OH)_2$	Over three days in April, 2008
Cane Parkway		2008			
Scanlon Creek Reservoir		2008			
Loch Flemington		2010	25 tonnes		Over three days in March, 2010
Bärensee		2007			

Physico-Chemical Aspects of Lakes Employing Phoslock® Treatment

Lake (multiple treatments)	Date Recorded		Total Phosphorus (mg P L^{-1})	Dissolved Inorganic Phosphorus (mg P L^{-1})	Chlorophyll a (µg Chl a L^{-1})	Cyanobacteria (cells mL^{-1})	Algae Count (cells mL^{-1})	Secchi Depth (m)	pH	Total Nitrogen (mg N L^{-1})	Nitrate (mg NO_3^- L^{-1})	Ammonium (mg NH_{4+} L^{-1})	Oxygen (mg O L^{-1})
Lakes treated only with Phoslock ®													
Lake Het Groene Eiland	2008-2010	**Referenced Lake**	0.036						8.4	2.45	3.07	0.06	11.8
	2008-2010	**Treated Lake**	0.029						8.4	0.68	0.27	0.05	10.8
Swan Lake	2011	**Pre-treatment**	0.247		32			0.47		2.7			
	2014	**Post Treatment**	0.06		12.6			1.4		1.1			
Laguna Niguel Lake	Varied	**Pre-treatment**	**2012** 0.260			**2013** 33,300		**2011** 61.6 **2012** 100.5 **2013** 122.6					
	2013	**Post Treatment**	~0.052			1,200							
Cane Parkway	2008	**Pre-treatment**	**Surface Water Column** 0.247 **Bottom Water**	0			200,000						
	2008	**Post Treatment**	**Surface Water Column** 0.075 **Bottom Water Column** 0.050	0.03			48,000						

Physico-Chemical Aspects of Lakes Employing Phoslock® Treatment

Lake (multiple treatments)	Date Recorded		Total Phosphorus (mg P L^{-1})	Dissolved Inorganic Phosphorus (mg P L^{-1})	Chlorophyll a (µg Chl a L^{-1})	Cyanobacteria (cells mL^{-1})	Algae Count (cells mL^{-1})	Secchi Depth (m)	pH	Total Nitrogen (mg N L^{-1})	Nitrate (mg NO_3^- L^{-1})	Ammonium (mg NH_{4+} L^{-1})	Oxygen (mg O L^{-1})
Scanlon Creek Reservoir	2008	**Pre-treatment**	**Surface Water Column** 0.080 **Bottom Water Column** 0.025	0.001			58,000						
	2008	**Post Treatment**	**Surface Water Column** 0.050 **Bottom Water Column** 0.050	0			60,000						
Loch Flemington	2009	**Pre-treatment**						<0.5					
	2011	**Post Treatment**						1.4					
Bärensee		**Pre-treatment**	0.08						8-9	2.1			
	2015	**Post Treatment**	0.052	0.016	14					0.94		0.08	

Physico-Chemical Aspects of Lakes Employing Phoslock® Treatment

Lake (multiple treatments)	Date Recorded		Total Phosphorus (mg P L^{-1})	Dissolved Inorganic Phosphorus (mg P L^{-1})	Chlorophyll a (µg Chl a L^{-1})	Cyanobacteria (cells mL^{-1})	Algae Count (cells mL^{-1})	Secchi Depth (m)	pH	Total Nitrogen (mg N L^{-1})	Nitrate (mg NO_3^- L^{-1})	Ammonium (mg NH_{4+} L^{-1})	Oxygen (mg O L^{-1})
Lakes treated with a combination of polyaluminum chloride and Phoslock ® ("Flock & Lock")													
Lake Rauwbraken	2008	**Pre-treatment**	0.091		12				7.7				
	2008	**Post Treatment**	0.019		3				7				

Physico-Chemical Aspects of Lakes Employing Phoslock® Treatment

Lake (multiple treatments)	Date Recorded		Comments
Lakes treated only with Phoslock ®			
Lake Het Groene Eiland	2008-2010	**Referenced Lake**	This study compared the test site to the larger surrounding reference site.
	2008-2010	**Treated Lake**	Orthophosphate and TP levels were not significantly different,TN and nitrate levels were significantly different.
Swan Lake	2011	**Pre-treatment**	Phoslock was able to effectively reduce internal P-loading.
	2014	**Post Treatment**	Continued phosphorus contributions by waterfowl will inhibit the Phoslock's effectiveness.
Laguna Niguel Lake	Varied	**Pre-treatment**	Post-treatment data was averaged over 4 sampling events during 2013
	2013	**Post Treatment**	
Cane Parkway	2008	**Pre-treatment**	
	2008	**Post Treatment**	

Lake (multiple treatments)	Date Recorded		Comments
Scanlon Creek Reservoir	2008	**Pre-treatment**	
	2008	**Post Treatment**	
Loch Flemington	2009	**Pre-treatment**	
	2011	**Post Treatment**	
Bärensee		**Pre-treatment**	Pre-treatment data was gathered from historic records
	2015	**Post Treatment**	Post-treatment data averaged over 8 sediment sampling events

Physico-Chemical Aspects of Lakes Employing Phoslock® Treatment

Lake (multiple treatments)	Date Recorded		Comments
Lakes treated with a combination of polyalumin			
Lake Rauwbraken	2008	**Pre-treatment**	The mixture "Flock & Lock" caused a temporary disapperance of Daphnia for 3 months.
	2008	**Post Treatment**	

References for Lakes Employing Phoslock® Treatment

Lake	References
Lake Het Groene Eiland	Lürling et al. 2012
Swan Lake	Nürnberg et al. 2016
Laguna Niguel Lake	Bishop et al. 2014
Lake Rauwbraken	Lürling et al. 2010
Cane Parkway	Moos et al. 2013
Scanlon Creek Reservoir	Moos et al. 2013
Bärensee	Epe et al. 2017