Aeration and Oxygenation Methods for Stratified Lakes and Reservoirs

Barry Moore, Mark Mobley, John Little, Bob Kortmann, and Paul Gantzer

Introduction – *Barry Moore*

> "The earth is like a spaceship that didn't come with an operating manual."
>
> ~ *R. Buckminster Fuller*

Buckminster Fuller was a great visionary thinker, architect, mathematician, and inventor. He is probably best known for the geodesic dome, which he promoted as one means of providing low-cost, highly efficient, and structurally sound human shelter. While only a small part of "Bucky's" prolific career, the geodesic dome has become a tangible symbol of his grander advocacy for the pursuit of rational solutions to the multitude of challenges that face humans on earth. As this famous quote implies, our fate is irrevocably tied to this planet; and we must learn how to pilot that ship if we are to arrive safely at our destination in the future.

While this may seem to be lofty, pie-in-the sky thinking, I have always felt that the adage, "Think globally; Act locally," has no better application than to lakes and watersheds. The phrase, variously attributed, has become the unofficial motto of Earth Day, and to me denotes that global environmental protection can only be achieved through widespread implementation of smaller scale actions.

Which brings me around to the NALMS Tampa conference; on first seeing speakers and topics for the Hypolimnetic Oxygenation sections, my mind was sliding along this global/local scale. Not only is that Earth operating manual not in the vehicle's glove compartment, all of the sections on terrestrial, marine, atmospheric, and freshwater systems are missing. For lakes, we do have the "Cooke (et al.)" book, pun intended, which summarizes collective efforts of lake scientists, at least up to 2005, to provide operating guidance for lakes. But for both in-lake and watershed management technologies, we are far from a standardized "cook book," with prescriptions for lake and reservoir design, operation, and maintenance.

Hypolimnetic Aeration and Oxygenation – *Barry Moore*

The technology of hypolimnetic aeration (HA) is now well over seven decades old. Many lake scientists have promoted HA as an in-lake technology for restoring dissolved oxygen (DO) levels without disrupting stratification, for restoring critical habitat, especially for cold-water fisheries, and for reducing internal loading of phosphorus and perhaps metals, such as manganese and mercury. Fishery benefits flow from hypolimnetic oxygen levels suitable for fish, but phosphorus and metal load reduction depend on adequate DO at the sediment/water interface (SWI).

Sizing methods for HA systems have been published, and a general outline has emerged (e.g., Lorenzen and Fast 1977; Ashley 1995; Kortmann, et al. 1994). A key first element in HA system design is determination of hypolimnetic oxygen demand, often expressed as oxygen deficit rate (ODR) that will need to be satisfied. However, even with calculation of ODR based on historical lake data, most practitioners have advocated use of a multiplication or safety factor to account for "induced oxygen demand." Even this first element of system design remains an empirical exercise, rather than a rational one based on the underlying physical, biological, and chemical processes.

Over the past two decades, emphasis has shifted from *aeration* to hypolimnetic *oxygenation* (HO). However, both HA and HO project numbers are far short of the situations where these technologies may be appropriate. Economics undoubtedly plays a role in this disparity, but the situation is starting to change, with more economical means for oxygen delivery, and because we are learning to better match system design with individual lake requirements. While oxygenation systems still do not come with an operating manual, the Tampa speakers made it clear that substantial progress has been made.

In this article, my coauthors and I describe progress in concept, design, operation, and performance of HO systems. I will describe our experiences with the first lake application of a saturation oxygenator; in this case, down-flow contact bubble oxygenation; otherwise known as a Speece Cone. Mark Mobley will describe his initial line-diffuser oxygenation experiments and how line-diffuser system design was developed and has been improved. The numbers of line diffuser installations have recently substantially multiplied, which perhaps portends a realization of the promise of widespread use of HO. John Little has been a pioneer in modeling oxygen transfer in both saturated and unsaturated HO systems. These models are requisite for system design, and John will describe how progress in modeling can lead to more successful HO applications. Paul Gantzer, a former student of John Little, has had extensive experience with cones and line diffusers, in terms of both design and performance assessments. Paul will describe his latest efforts to compare the ability of these systems to deliver oxygen to the SWI, which has long been viewed as the crucial link for internal phosphorus reduction with HO. Bob Kortmann has been a long-time advocate for understanding energy flows in lake management (Kortmann and Rich 1994 should be required reading for lake scientists ,in my view). Bob will discuss layer aeration, which he describes as a "depth-selective artificial circulation method" that manipulates stratification structure, without destratification, and manages the interface between trophogenic and tropholytic zones, where DO is, respectively, produced and consumed. Layer aeration may be employed to manipulate thermocline depth, and thus hypolimnetic volume, which can be useful for making other HO or HA approaches more cost-effective and efficient.

Hypolimnetic Oxygenation in Newman Lake: Speece Cone – *Barry Moore*

The story of HO in Newman Lake, first implemented in June 1992, is especially illustrative of the need for better operating information, but also illustrates the period of transition from HA to HO technology. Details of over 30 years of our restoration research on Newman Lake can be found in a series of three papers in *Lake and Reservoir Management* (Moore and Christensen 2009; Moore et al. 2009; Moore et al. 2012). Dr. Bill Funk, director of the State of Washington Water Research Center, first investigated causes of cyanobacteria blooms in Newman Lake that appeared in the 1960s. Unfortunately, his recommendations for addressing the problem went unheeded, and blooms increased in severity and frequency through the 1970s and 1980s. My own graduate studies under Dr. Funk's mentorship began in 1979; in 1986 we published a Phase I Diagnostic/Feasibility study that recommended alum treatment, hypolimnetic aeration, and various watershed nutrient reduction efforts to address internal and external phosphorus loads that were driving the water quality problems (Funk and Moore 1988).

Citizens of Newman Lake took up the charge, and, working through the Newman Lake Flood Control District (NLFCD) and Spokane County Engineers Office, successfully obtained a Phase II Implementation grant from the Washington Department of Ecology (WDOE). When the Phase II plan was conceived, there were a number of off-the-shelf, turnkey HA systems on the market. However, by the time the Phase II grant was in place, this was no longer the case, necessitating that we put together a design team to explore HA options. A key member of this team was Dr. Ken Ashley, who had directed numerous full- and partial-lift HA systems in British Columbia. With the off-the-shelf option removed, we turned to Bernhardt-style, full-lift aerator designs. Our calculations quickly revealed that Bernhardt aerators would necessitate four to five large surface units to satisfy oxygen demand; it was clear that technical, economic, maintenance, and even aesthetic considerations made this option very impractical.

Ken suggested that we consult Dr. Richard (Dick) Speece, emeritus professor from Vanderbilt University, who had published theoretical designs for oxygenators that could potentially be adapted to lake environments. Ultimately, following Dick Speece's lead, we settled on a design for a "down-flow contact bubble aerator," aka the "Speece cone," using pure oxygen for the Newman application. In the early 1990s, there had been only a few Speece cone installations, in fish hatchery and dam tail-water aeration applications. Newman Lake represented the first application of Speece cone technology in lake restoration. The system was designed to deliver 1,360 kg of oxygen daily to the hypolimnion. Other "firsts" characterized the Newman Lake system, including first use of a discharge manifold designed to enhance oxygen distribution in the hypolimnion while preventing sediment entrainment, and first use of on-site, pressure swing adsorption (PSA) for the oxygen source. Dual compressors/PSA units were located onshore to pump oxygen to the submerged cone (Figure 1), providing some operational flexibility in daily oxygen delivery rates.

With no operating manual, we proceeded with a plan to start the HO system in spring as soon as thermal stratification was detected. Spring start-up was done with one compressor at 50-percent capacity. As hypolimnetic monitoring detected declining DO, the other compressor was started bringing the system up to 100-percent capacity. The goal was to obtain benefits of higher hypolimnetic DO while minimizing costs; unfortunately, several problems were soon manifest. For one, the system was never able to "catch up" with the oxygen demand; even at full capacity, hypolimnetic oxygen began to decline, and by mid-July we typically observed complete anoxia in the bottom 2 to 3

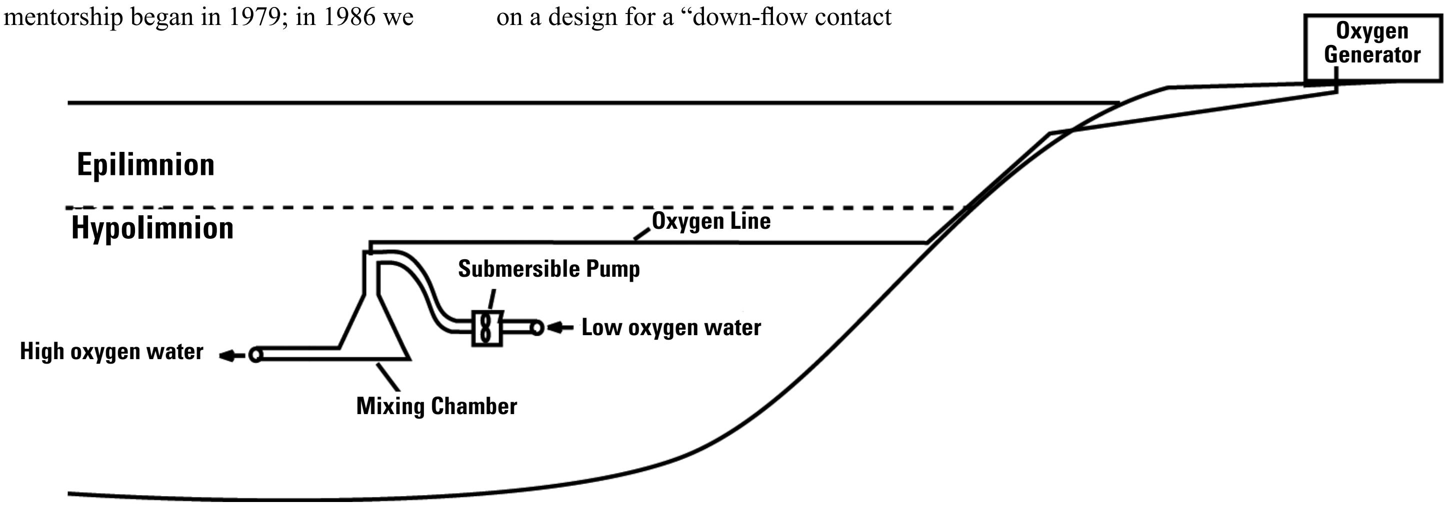


Figure 1. Diagrammatic view of the Newman Lake downflow contact bubble aerator (Speece Cone) system (not to scale).

meters of the lake. Obviously, this would preclude realization of targeted internal phosphorus load reduction.

To understand why the initial partial oxygenation plan would not work, we conducted a series of laboratory experiments on anoxic Newman sediments (detailed in Moore et al. 1996). As noted above, design equations for HA and HO have always been empirical and have included a safety (i.e., fudge) factor to account for increased post-oxygen demand, compared to measured, pre-oxygenation rates. For in the Newman system, we used a factor of about three times observed ODR. Oxygenation systems move water in the usually static hypolimnion, which is believed to be the source of this "induced oxygen demand". Our experiments clearly showed increased oxygen demand with increased water velocity at the SWI.

Consequently, starting in 1997, we altered operational protocols, starting the system at full capacity concurrent with stratification development. Unfortunately, spring 1997 brought a "perfect storm," the culmination of a series of environmental events that tremendously impacted the lake for the next few years. These events included massive ice storm damage to the watershed, followed by record snowfalls, then warm spring temperatures and April rainstorms that produced a 100-year-plus flood event in Thompson Creek, the primary Newman tributary (Marianne Barrentine, Spokane County Engineers Office, 2008, personal communication based in USGS, NRS, and county records). The April 1997 floodwaters were cold, close to 4ºC, and were extremely turbid, being filled with ice storm-damaged soils and debris. The lake immediately stratified with an especially steep thermocline at about 3m, and with a hypolimnion full of sediment. I conducted multiple dives in Newman Lake that April and through the summer; visibility in the hypolimnion was absolutely zero, with no light penetration beyond the thermocline. Secchi depth from the surface never exceeded 1.5 m and was less than half a meter for most of the summer.

Implications for the HO were two-fold. First, hypolimnetic volume for 1997 was the highest observed in the 29 years of available data, at least 3 to 5 times that used for ODR calculations (Figure 2).

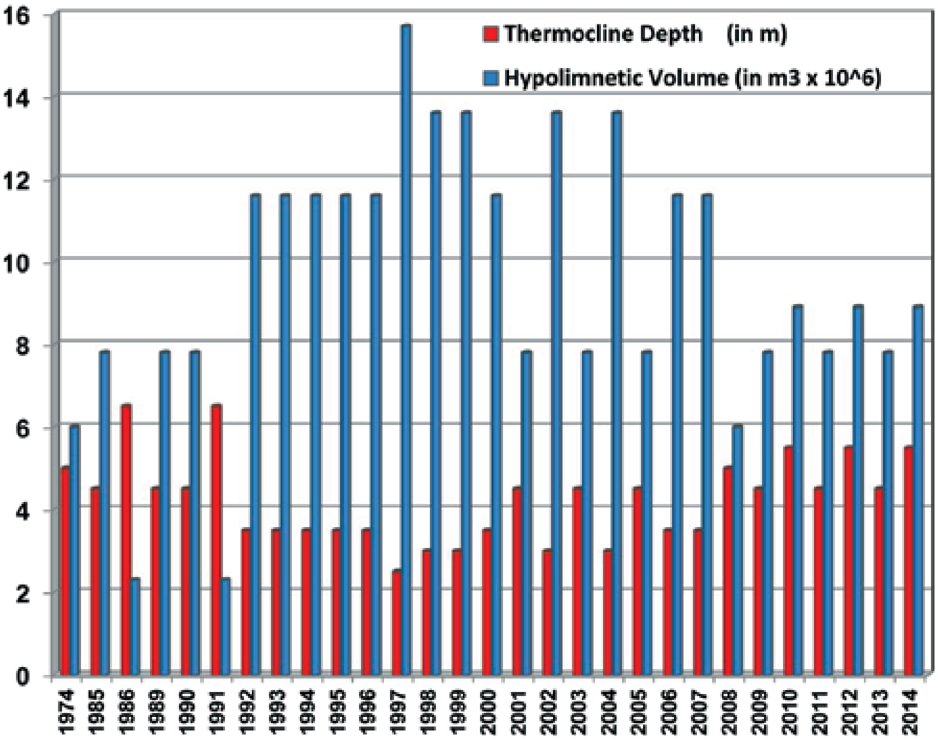


Figure 2. Thermocline depths and mid-summer hypolimnetic volumes for Newman Lake for all years with sufficient data for calculation, 1974 to 2014. Depths are in meters, and volumes of in millions of cubic meters.

Second, the extreme sediment loads likely multiplied total hypolimnetic oxygen demand for at least two years. Between these unusual environmental events and the initial operational decisions, the net result was that HO at Newman Lake was not operated within its total design ranges until 1999. We observed good DO levels in the lake that year, but unfortunately, the in-lake pump suffered a major breakdown in 2000; repairs took all summer, and precluded operation for the critical stratification season.

The catalog of these operational and environmental events is essential for understanding Newman Lake response to HO, which can be tracked by the Nürnberg anoxic factor (AF) (Nürnberg 1995). AF indices for all years with sufficient data for calculation show good response to HO since 2001 (Figure 3). The steady improvement in AF has been accompanied by improved water quality, as evidence by vastly decreased peak and average algae concentrations, lowered total phosphorus, increased transparency, and excellent control of the cyanobacteria blooms (see references noted above). Improving AF at Newman also coincides with our diver observations of declining organic matter in the sediments; as will be addressed further in Paul Gantzer's discussion.

To summarize the lessons from Newman: Early attempts to save money by partial operation were unsuccessful as anoxia was not overcome at the SWI; we could never "catch up" with the oxygen demand by delaying full capacity operation and the associated economic "savings." Expressed in a manner often necessary to inform bureaucrats and the public, economic savings of 50% *do not* provide 50% water quality benefits.

In addition, legacy oxygen demand, stored as labile sediment organic matter, took years to diminish. Lake ecological response to improved DO at Newman Lake was initially slow, but appears to be improving; the improvements seem to track reduction in sediment organic matter. I also believe that Newman vividly demonstrates the value of pre-restoration monitoring. We are lucky to have data from a year with average hypolimnetic volume close to the 30-year average. However, had the study been conducted in another year, over-or under sizing the HO system would result in inappropriately high capital costs or

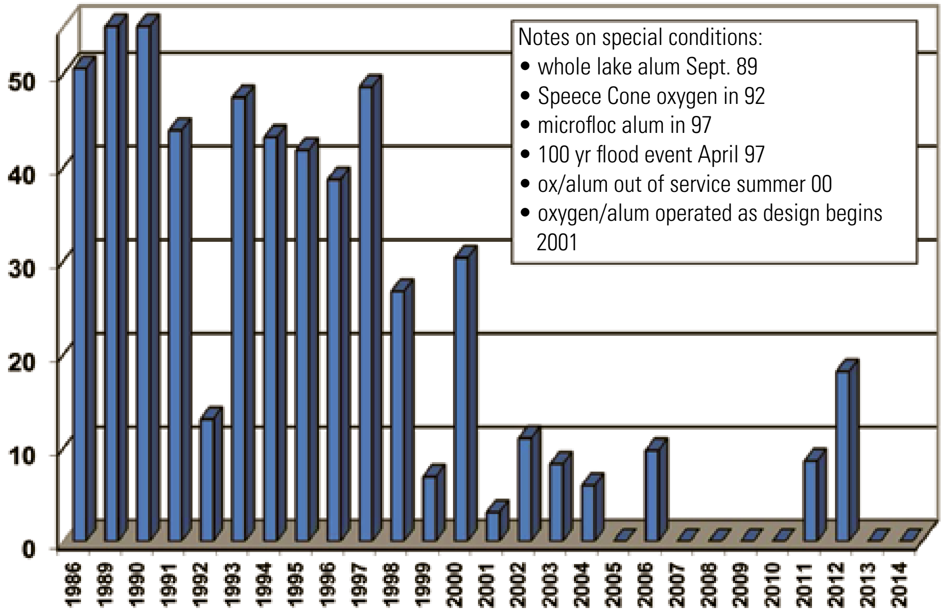


Figure 3. Nürnberg Anoxic Factors (AF) in Newman Lake, for all years with sufficient data for calculation, 1986 to 2014. AF in days^{-1}, and calculated as dissolved oxygen less than 2 mg/L at 1 m above the sediment water interface. See Nürnberg (1995) for details.

probable ineffectiveness. Communities need to be informed that adequate pre-design monitoring is not only a sound, but an essential, investment.

Line Diffuser Development - Mark Mobley

Water quality of reservoir releases became a recognized issue for hydropower projects in the 1970s. Many Federal Energy Regulatory Commission (FERC) licensing requirements now include minimum DO standards and projects owned by Federal agencies are under pressure to improve downstream water quality and to address low DO in hydropower discharges. A good example of responses to these environmental concerns is provided by the Tennessee Valley Authority's (TVA) Lake Improvement Plan, completed in 1997, that improved minimum flow and DO at 16 hydropower projects. These projects were the impetus for several new and innovative aeration alternatives, including the *porous hose line diffuser*. TVA first employed reservoir oxygen diffusers to supplement other DO delivery methods and as a standalone enhancement when less expensive options were not applicable.

The porous hose line diffuser distributes gas bubbles to introduce DO in the water column. Rising gas bubbles can impart DO into the surrounding water, and can be used to induce whole-lake circulation, thereby improving oxygen exchange with the atmosphere, much as in an aquarium. However, line diffusers may also be used in situations where maintenance of thermal stratification is desired. This is the case with many reservoir, as well as lake, applications (Figure 4). As with Speece cones and other saturated systems, onshore facilities supply compressed air or oxygen to the line diffusers.

For hydropower applications, pure oxygen is preferred to avoid potential total dissolved gas problems in the tailrace. These systems can be quite large, e.g., 200 tons per day at the US Army Corps of Engineers' Richard B. Russell hydro project. Purchasing enough oxygen to increase the DO of large-scale hydropower water flows can be very expensive. To reduce costs, early research and pilot tests focused on obtaining high oxygen transfer efficiency. Researchers first experimented with ceramic fine pore diffusers, as they could generate very fine bubbles, optimizing the surface area for oxygen transfer efficiency. Unfortunately, ceramic diffusers worked great in the lab but displayed a strong tendency to clog in actual field installations. At the Richard

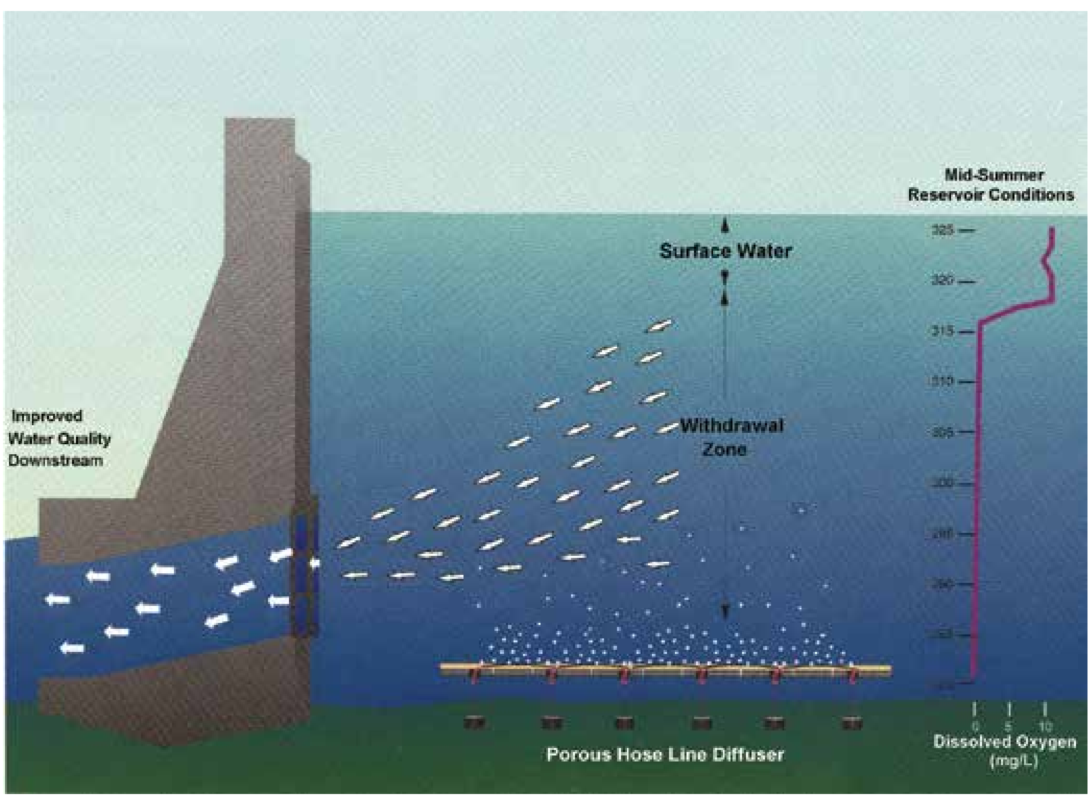


Figure 4. Reservoir oxygen diffuser for hydropower application (Graphics – TVA).

B. Russell system hydrogen chloride gas injection was used to clean the ceramic diffusers, but the maintenance expenses for ceramic diffusers led to a search for other diffuser designs.

When I first got involved in 1988, we installed three steel diffuser frames for a pilot oxygenation system on Unit 4 at TVA's Douglas Dam. Each 6 meter by 10 meter (20 foot by 33 foot) frame supported 78 membrane diffusers (Figure 5). Early tests were positive, confirming DO enhancement of about 2 mg/L, with oxygen transfer efficiency of 72%. However, the tight packed diffuser arrangement produced overly vigorous bubble plumes that entrained nearby sediments. This led to greater induced oxygen demand and clogged the generator cooling systems with sediments and organic growth, necessitating outages for cleaning and chemical treatments. These experiences clearly indicated the need to spread bubbles over larger areas to reduce mixing and sediment entrainment.

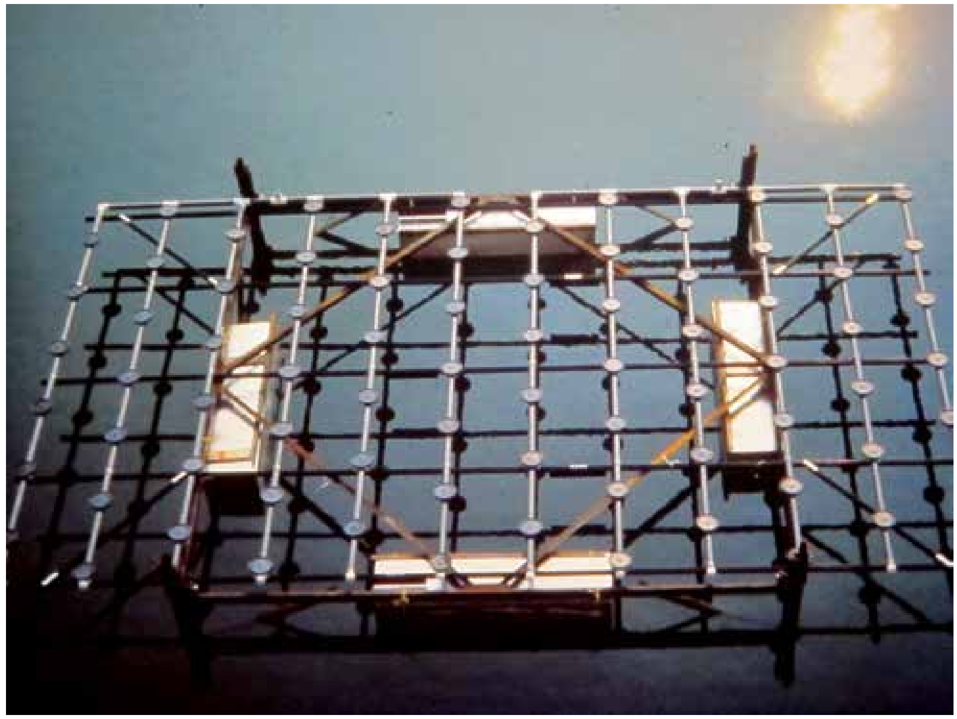


Figure 5. Pilot scale oxygenator frame at TVA's Douglas Dam with steel diffusers, 1988.

The problem was put to a TVA Engineering Laboratory team that eventually hit upon the idea of using garden-variety (literally) soaker hose. Soaker hose was readily available at home improvement and irrigation supply stores, was made partly of recycled tires, and best yet, it made beautiful bubbles. In initial tests, we put the same oxygen flow through 50 linear feet of porous hose as had previously been applied to one 9-inch diameter diffuser head. This spread the bubbles, creating a weak plume that neither entrained sediments nor disrupted stratification (Figure 6). Slower bubble rise also created more contact time, and the thin long linear plumes make it more likely for the bubbles to be directly in contact with ambient water. These characteristics combined to provide high oxygen transfer efficiency, improving transfer at Douglas to about 85%.

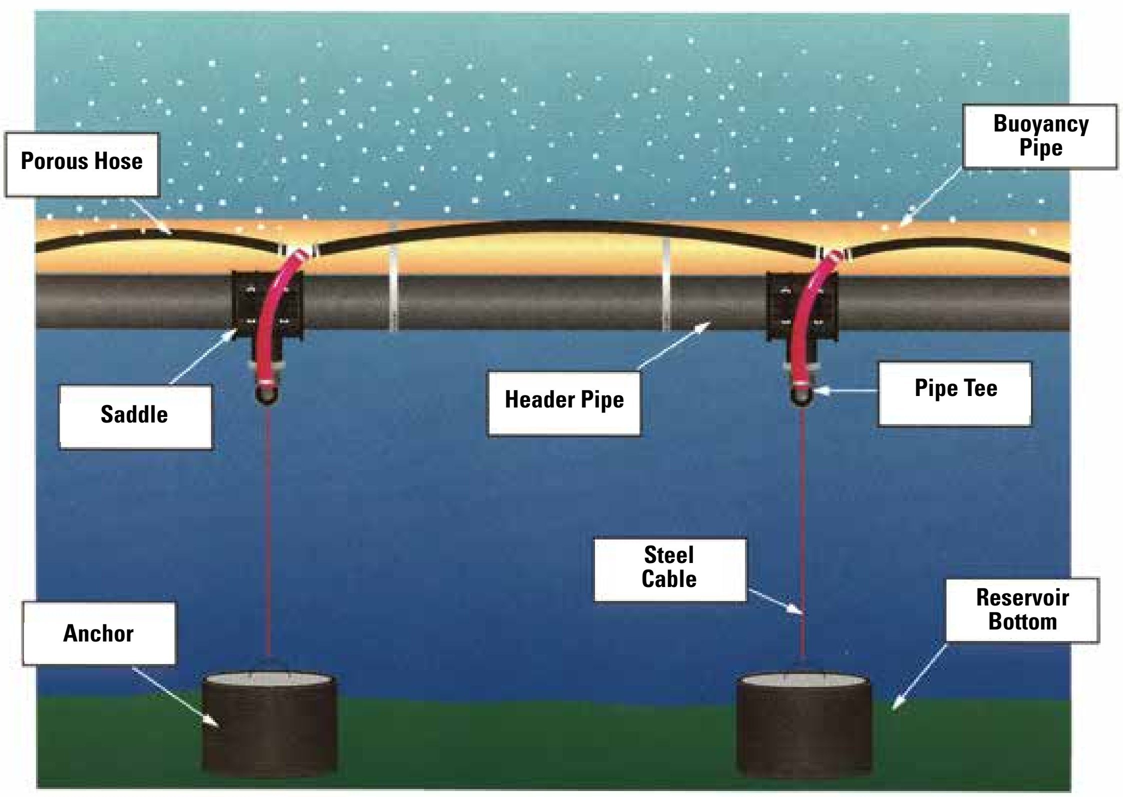


Figure 6: Line diffuser construction details (Graphics – TVA).

We next needed to work out how best to deploy soaker hose diffusers in a reservoir. Several iterations of huge PVC pipe frames later, we finally arrived at a single line arrangement designed to fit a deep, narrow channel reservoir (Mobley et al. 2000). The single line actually consists of a high-density polyethylene (HDPE), two-pipe design. One pipe supplies the gas and the other is used for buoyancy. Concrete anchors are deployed at 15-foot intervals and two porous diffuser hoses run the full length of the installation (Figure 6). With the buoyancy pipe filled with air, the entire diffuser and anchor assembly will float, and can be maneuvered with boats to the desired location. Deployment is accomplished by simply filling the buoyancy pipe with water, sinking the assembly. If maintenance is required, this process is reversed by filling the buoyancy pipe with compressed air, allowing for easy retrieval and access at the surface. This single line, two-pipe arrangement has proved to have many advantages including; economical components, simplicity of assembly, ease of deployment/retrieval without divers, and flexibility of application. Over the past decade, line diffuser design has evolved with changes to make the systems more robust and easier to assemble and deploy in the field.

The system is also highly adaptable to specific conditions for a wide range of applications. In 1996 at the Minneapolis NALMS Symposium, I had a conversation with Dr. John Little of Virginia Tech about using line diffusers for water supply reservoirs. Our first such application was in Roanoke, Virginia, and the design has now been employed in water supply reservoirs all over the U.S. In 2009, we installed a line diffuser at Twin Lakes, Washington, which was the first such application in a natural lake (Dent et al. 2014; Moore et al. 2014; Skinner et al. 2015). Line diffusers have now been applied at over 20 hydropower projects (Crutchfield et al. 2012; Mobley et al. 2012), over 20 water supply reservoirs and several natural lakes as well as other applications.

To be effective, placement of reservoir diffusers and distribution of oxygen input from bubble plumes must be designed to meet site-specific water quality and water flow conditions (Figure 7). Oxygen placement requirements have ranged from placing oxygen in the withdrawal zone of hydropower turbines, to blanketing reservoir sediments, or to placing oxygen in a specific temperature zone for fish habitat. Bubble plume requirements have ranged from weak widely distributed plumes that would not disrupt reservoir stratification to full reservoir volume destratification systems. To do that, a lot had to be learned about bubble plumes and cold-water detrainment in stratified water bodies.

Figure 7: One of nine line diffusers at J. Strom Thurmond Reservoir (U.S.A.C.E. Savannah District) used to create fish habitat for striped bass as mitigation for pumped storage hydropower operation.

Model Development – *John Little*

Properly designed hypolimnetic oxygenation systems can replenish DO in water bodies while preserving stratification (Singleton and Little 2006). Three primary designs are the airlift aerator, Speece Cone, and bubble-plume diffuser (Figure 8). Airlift aerators typically consist of a vertical riser tube, a diffuser inside the bottom of the riser tube, an air-water separation chamber at the top of the riser, and one or two return pipes, called downcomers. Compressed air is delivered to the aerator and bubbles freely from the diffuser. This creates a positively buoyant gas/water mixture that ascends the riser. At the top of the riser, bubbles are released to the atmosphere, and some may be entrained in the water that enters the downcomers. Oxygenated water descends in the downcomers and is returned to the hypolimnion.

The Speece Cone consists of a source of oxygen gas, a conical bubble contact chamber, a submersible pump, and a diffuser that disperses highly oxygenated water into the hypolimnion. Ambient water and oxygen gas bubbles are introduced at the top of the cone. As water flows down the cone, the velocity decreases because the cross-sectional area of the cone increases. The system is designed so that downward velocity of water at the top of the cone is sufficient to overcome the rise velocity of the oxygen bubbles. At the cone bottom, water velocity is less than the rise velocity of the now smaller bubbles. Applied water flow rate and slope of the cone walls control water velocity and, therefore, time available for gas transfer.

Bubble-plume diffusers are generally linear or circular and inject either air or oxygen at a relatively low gas flow rate. Gas bubbles are injected into the water column through a porous diffuser creating a gas/water mixture that rises and gains momentum due to positive buoyancy. The buoyant mixture entrains water at the boundaries, which increases the water flow rate and cross-sectional area, but decreases the momentum. The plume rises against the vertical density gradient until the depth of maximum plume rise is reached, which is where the plume momentum is zero. Plume water at this

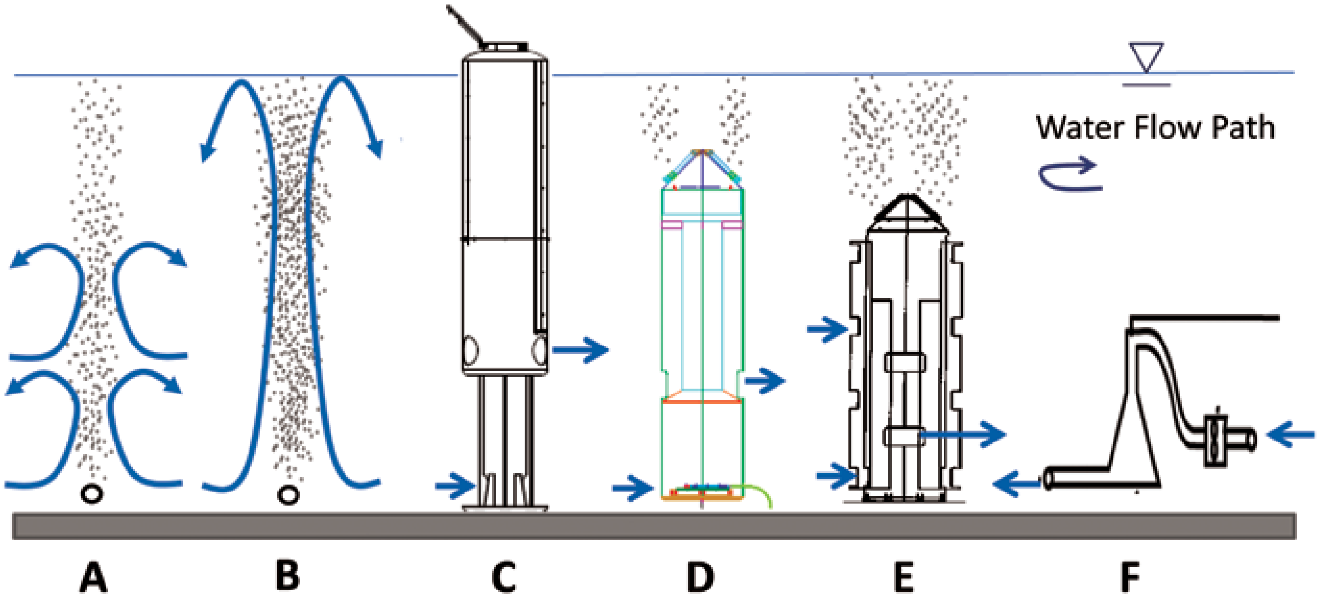


Figure 8. Schematic diagrams of aeration and oxygenation techniques for managing lake community respiration and sediment-water interactions, including: (A) line diffuser with low enough gas flow to maintain stratification, (B) line diffuser with high enough gas flow to prevent stratification, (C) traditional full-lift hypolimnetic aeration, (D) submerged partial-lift hypolimnetic aeration, (E) depth-selective layer aeration, and (F) conical oxygen contactor, aka "Speece Cone."

depth is negatively buoyant and tends to fall back to an equilibrium depth where the plume density equals the ambient density. Upon reaching the equilibrium depth, the plume water intrudes back into the ambient water. These systems are most suitable for deep lakes where the bulk of the generated bubbles dissolve in the hypolimnion and the momentum imparted by the plume to the surrounding water is low enough to prevent significant thermocline erosion.

In each of these three devices, gas bubbles in contact with water facilitate interfacial transfer of oxygen, nitrogen, and other soluble gases; and they usually alter the thermal structure of a waterbody. However, early design procedures for airlift aerators were empirical, while most bubble-plume models did not account for stratification or gas transfer. Oxygen transfer efficiency is a function of the surrounding water column properties, establishing a feedback loop that continually changes system performance. This effect is most pronounced during operation of bubble-plume diffusers because plume performance depends strongly on the vertical density gradient. The interaction of the aerator/oxygenator with the water column should be accounted for in the design and operation of bubble-plume diffusers, as well as the other aeration and oxygenation devices.

Using fundamental principles, a discrete-bubble model was first developed to predict plume dynamics and gas transfer for a circular bubble-plume diffuser. The discrete-bubble approach has subsequently been validated using oxygen transfer tests in a large vertical tank (McGinnis and Little 2002) and applied successfully at full-scale to an airlift aerator (Burris et al. 2002) as well as to both circular (McGinnis et al. 2004) and linear (Singleton et al. 2007) bubble-plume diffusers. The combined results suggest that the models can be used with some confidence to predict system performance based on applied air or oxygen flow rate and the initial bubble size. The unified suite of models, all based on simple discrete-bubble dynamics, represents the current state-of-the-art for designing systems to add oxygen to stratified lakes and reservoirs (Singleton and Little 2006). Effective design and operation of hypolimnetic oxygenation systems is difficult to achieve without the use of hydrodynamic models.

Layer Aeration – *Bob Kortmann*

As the supply of organic matter to a lake increases in response to eutrophication, respiration in the lake increases. As respiration increases, so demand for terminal electron acceptors in respiration increases (oxygen in aerobic organisms). In deep lakes during summer, thermal stratification limits the input of atmospheric oxygen. Respiration consumes oxygen faster than can be replenished. With the loss of DO anaerobic respiration leads to nutrient build-up and to accumulation of anaerobic respiration products such as carbon dioxide, iron, manganese, and sulfides. Eutrophication accelerates. A variety of aeration and oxygenation methods have been developed to increase a lake's aerobic respiration capacity.

While the discussions above have focused on HA and HO, the first method employed to address eutrophic oxygen depletion was artificial circulation Figure 8 (B). Artificial circulation may be accomplished by diffused airlift pumping or by mechanical mixing; the principal is to prevent development of thermal stratification. This strategy works best in nutrient-rich lakes, where nutrient control is not feasible, when oxygen depletion is a threat to warm water fisheries, and for control of metals accumulation. Lake temperature is homogenized which can adversely impact cold-water fishery habitat and zooplankton refuge. Bottom temperature is increased, which accelerates respiratory DO demand. Artificial circulation eliminates the use of depth-selective supply withdrawal for optimizing raw water quality from distribution reservoirs. The benthic flux of dissolved constituents from sediment-interstitial to overlying waters is driven by Fickean diffusion and is a function of the concentration gradient across the sediment-water interface. Perhaps the most important, and least well known, impacts of artificial circulation are:

- intensification of concentration differential at the benthic interface, which increases flux of a variety of pore-water constituents (Kortmann, 1980), and
- homogenization of the trophogenic and tropholytic zones (destratification).

During the early 1980s *layer aeration* was developed to manage aerobic respiration capacity of a lake and related water quality relationships (Kortmann et.al. 1994). Layer aeration may be viewed as a "hybrid" of artificial circulation and HA. Rather than destroying stratification, or adding dissolved oxygen under it, layer aeration adjusts how stratification develops. Eutrophication increases primary productivity, which increases respiratory rate and oxygen demands. HA, HO, and layer aeration methods manage those respiration impacts.

To accomplish layer aeration, water is drawn into the aerator from both a warmer, oxygen-rich depth and a colder, oxygen-deficient depth. Those waters are blended returned at an intermediate depth and temperature (density), which creates an isothermal layer in the middle of the water column with thermoclines above and below. Layer aeration circulates a selected vertical depth range from the bottom of the trophogenic zone, where net photosynthetic oxygen production occurs, into the top of the tropholytic zone, net oxygen consumption. Hence, oxygen produced by photosynthesis is used to help meet respiratory oxygen demand. By computing the mass of heat and dissolved oxygen in vertical depth strata through the summer, one can forecast the temperature and DO content of the mixed layer, and thus the resulting stratification structure.

The first large-scale layer aeration system was implemented at Lake Shenipsit, Connecticut, a large recreational fishery lake used as a source of supply to north-central Connecticut. During the late 1970s, blooms of *Anabaena sp.* and *Aphanizomenon sp.* were stimulated by oxygen loss and internal cycling of nutrients (especially sediment-released soluble reactive phosphorous (SRP)). Nearly all cold water habitat for fish and herbivorous zooplankton refuge was lost during the summer. The blooms caused water supply treatment problems including taste and odor episodes, early exhaustion of activated carbon beds, and elevated chlorine demand. Response of the lake ecosystem to layer aeration occurred over a number of years, beginning with physical changes (Figure 9), then transparency and light penetration (Figure 10), followed by reduced nutrient availability and changes to the phytoplankton community (Figures 11 and 12). Within three years, the summer Cyanobacteria blooms subsided, over 3000 acre-ft of cold water habitat was restored, and zooplankton grazer populations increased. Summer transparency increased from 4 ft to 4 meters (13 ft). Dissolved oxygen has been maintained to 14 m (45 ft) since 1990.

Layer aeration has been very useful for:

- creating high quality mid-depth layers at intake depths in water supply reservoirs (protected from phytoplankton above and anaerobic respiration products below), and
- maintaining cool aerobic habitat for fish and as zooplankton refuge.

Lake Shenipsit Dissolved Oxygen (mg/L Before and During) Layer Aeration

Secchi (m)	1.3 m	4.0 m
Depth (m)	7/22/1985	7/22/1993
0	8.5	8.7
1	8.6	8.5
2	8.2	8.2
3	8.6	8.2
4	8.6	8.1
5	5.3	7.9
6	1.3	6.7
7	0.4	5.7
8	0.1	5.6
9	0.1	6.1
10	0.1	6.5
11	0.1	5
12	0.1	4.2
13	0.1	3.6
14	0.1	2.9
15	0.1	2.7
16	0.1	1.9
17	0.1	0.8
18	0.1	0

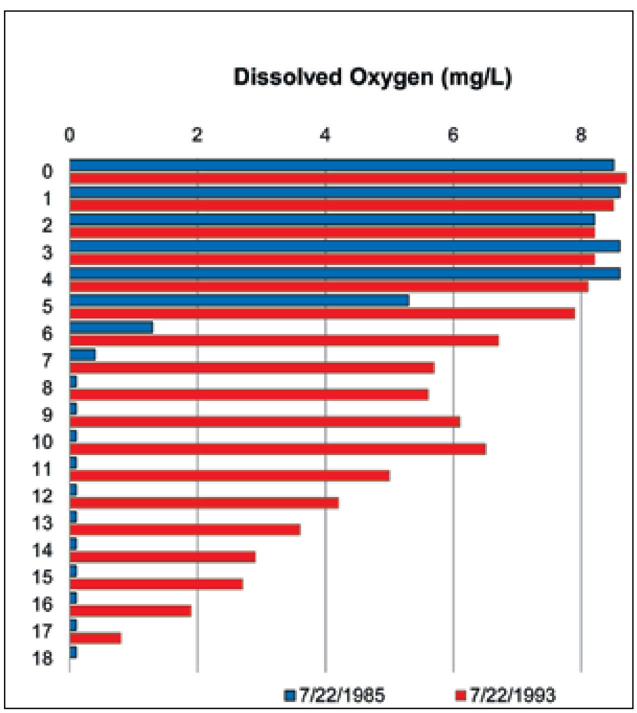


Figure 9. Depth profiles of dissolved oxygen at Lake Shenipsit before and during layer aeration, and a photo of a layer aeration tower (from Lake Waramaug, CT).

	Mean Summer Secchi	Anoxic Depth
1985	1.3	5
1986	1.4	6
1987	2	12.9
1988	2.5	16
1989	2.7	18
1990	5.2	19
1991	4.9	17
1992	4.6	18
1993	4.9	18
1994	5.2	17
1995	5	18
1996	5	17

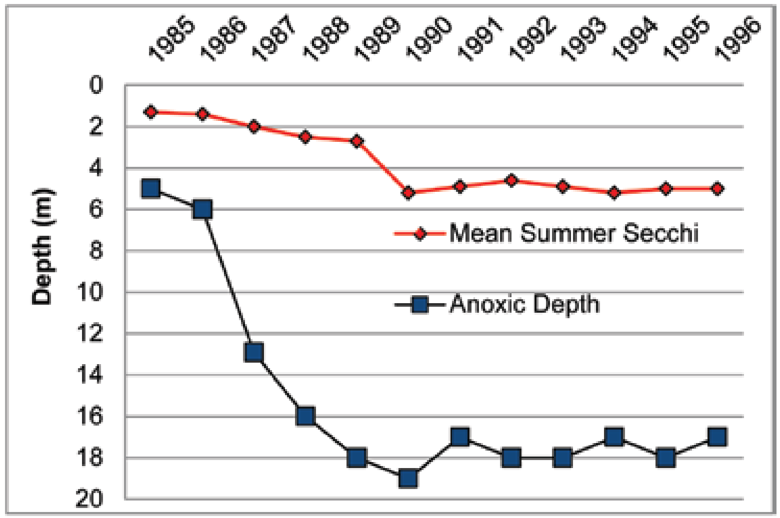


Figure 10. Response of Secchi disk transparency and depth of the anoxic boundary at Lake Shenipsit during the first decade of layer aeration.

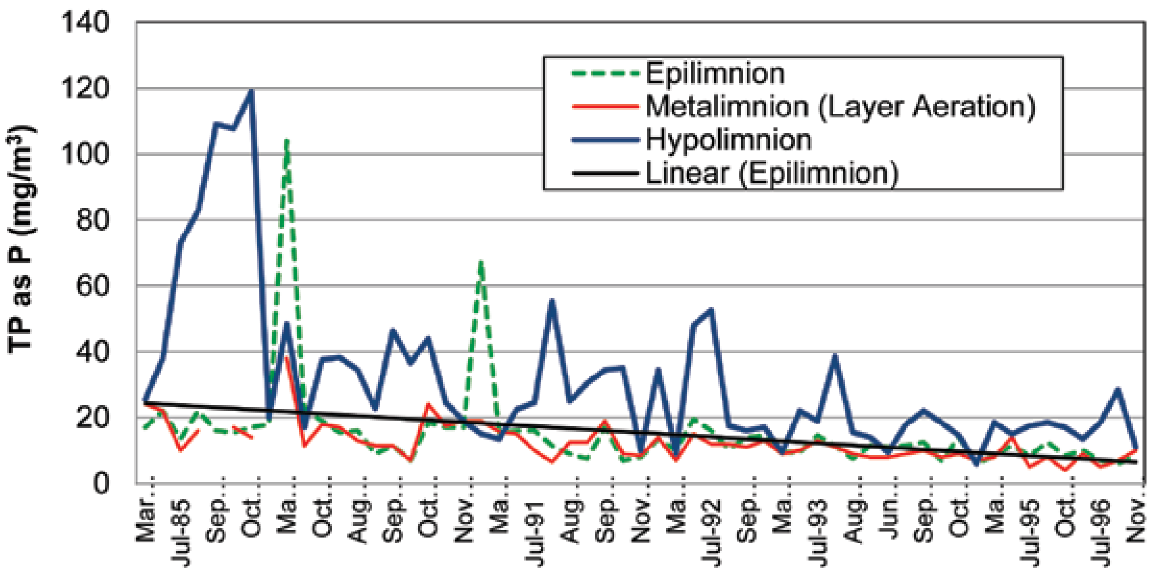


Figure 11. Response of Total Phosphorus concentrations in the epilimnion, metalimnion, and hypolimnion during the first decade of layer aeration at Lake Shenipsit.

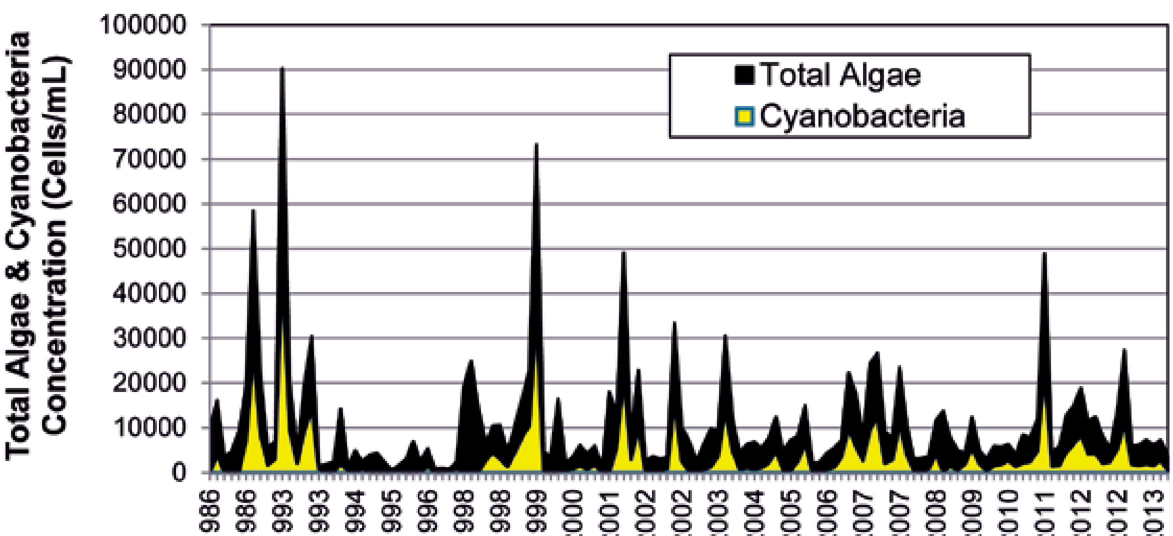


Figure 12. Changes in phytoplankton density and composition at Lake Shenipsit, 1986-2013.

- Reducing the impact of sediment-P release on the phytoplankton community
- Reducing the area and volume of the hypolimnion below the mixed layer, which can then be aerated/oxygenated very efficiently.

More than 25 layer aeration projects have been installed across the U.S. About two-thirds are source water supply reservoirs. Because layer aeration is an artificial circulation technique focused on a mid-depth layer, airflow requirements are typically less than needed for full water column destratification. Layer Aerators can be driven by compressed air (most common), enhanced air (>21% oxygen), or can be configured as downflow gas contactors (analogous to the Speece cone) for oxygenation. Several are off-grid and/or wind-powered.

HA/HO System Selection and Operation – *Paul Gantzer*

Once the decision is made to remediate hypolimnetic oxygen content, it becomes a matter of determining how to obtain an oxygen supply, and then to select the best delivery method for the particular water body. Oxygen can be obtained in liquid form (LOx) or by on-site generation (e.g., PSA mentioned for Newman Lake). This is a purely economic decision, and should incorporate figures for purchasing and transport of liquid oxygen, versus pressure-swing on-site oxygen generation, with costs from both amortized over expected life span of the system.

For oxygen delivery to the hypolimnion, there is a general dividing line, based on depth, between applicability of the Speece cone or line diffuser systems. Speece cones have significantly higher initial capital and long-term operating costs, associated with both the submerged water pumps and onshore compressor(s). However, although line diffusers have been deployed in depths as shallow as 10 m (30 ft), their oxygen transfer efficiency is greatly reduced at these shallow depths. Therefore, the system choice essentially depends on balancing higher capital and electrical cost for Speece cones versus the ability to deliver sufficient hypolimnetic oxygen to meet design goals for line diffusers. For depths greater than 45 feet, line diffusers have been observed to achieve oxygen transfer efficiencies greater than 90% so Speece cones systems are considered less economically justifiable in deeper water bodies.

There is however, ongoing debate about relative abilities of these systems to actually deliver oxygen to sediments and to maintain an oxic soil water interface (SWI). Oxygen status at the SWI has long been demonstrated as critical for control of internal load. Oxygen penetration into sediments may also be crucial to oxidize legacy sediment oxygen demand (SOD), which is the root of hypolimnetic anoxia. It is also hypothesized that HO systems begin to oxidize legacy sediment organic matter through years of operation, the reduced SOD begins a positive feedback in the lake. That is reduced SOD yields less internal phosphorus load, less annual primary productivity, less hypolimnetic oxygen demand from decreased SOD, and so on.

A central reason for the debate centers on the fact that Speece cones discharge highly oxygenated waters directly over sediments, although over a relatively small area. Away from the direct influence of the discharge header in the near field, oxygen distribution relies on natural dispersion and internal mixing characteristics from natural seiching. In contrast, line diffusers discharge oxygen over very long distances and the initial velocity is directed away from the sediments. However, the rising bubble plume from a line diffuser entrains surrounding water. When this plume encounters the thermocline, buoyancy forces the plume to spread laterally and then to sink, inducing a pumping action that may actually be more efficient at delivering oxygen beyond the near field, compared to dependence on natural mixing used by the Speece Cone (Figure 13).

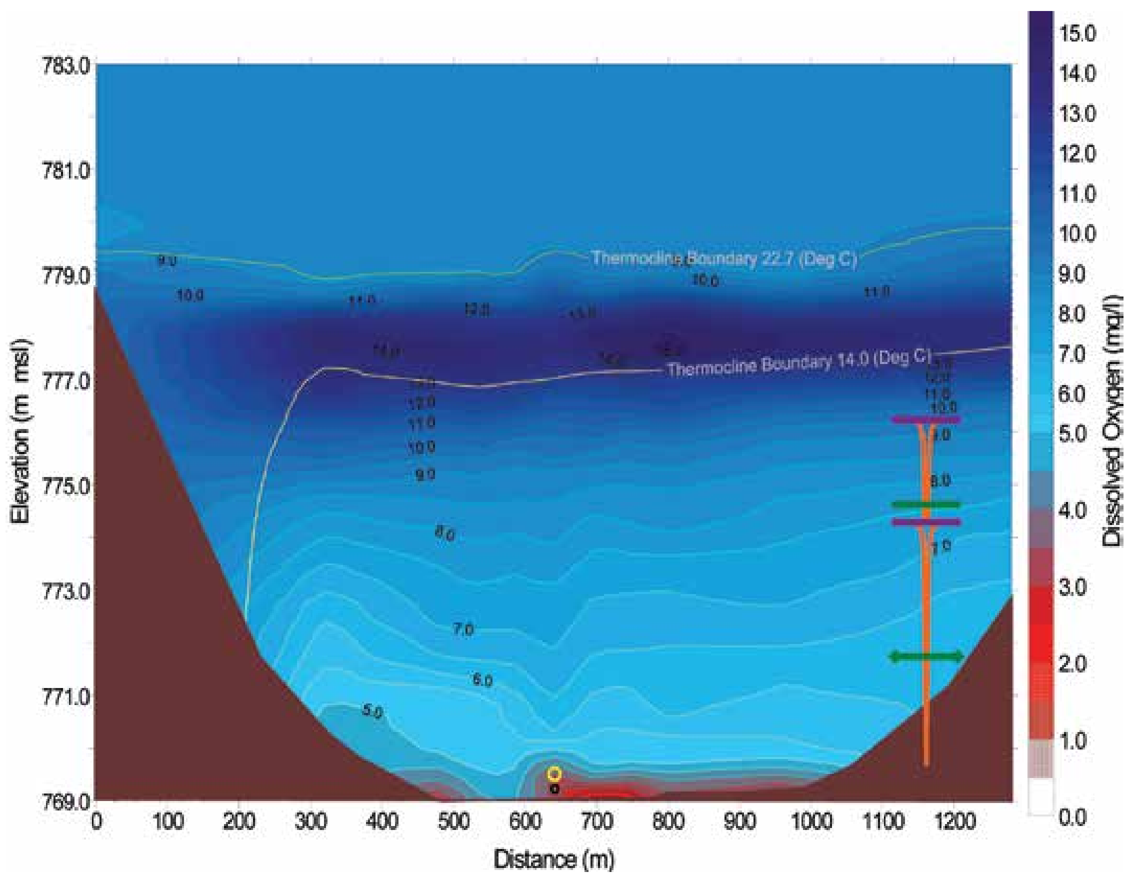


Figure 13. Oxygen distribution in North Twin Lake showing complete spreading of the oxygen throughout the entire basin as well as positive oxygen readings within the bottom 0.25-0.5m of the water column.

We recently performed tests to compare oxygen distribution in line diffuser and Speece cone systems in North Twin in Inchelium, WA and Newman Lake in Newman, WA, respectively. For the line diffuser, our results indicate strong oxidizing conditions within 0.1 m (6 inches) of the sediments at distances as far away as 150 m (500 ft), which matched the oxygen conditions observed at the same distance away from the Speece Cone discharge header (Figure 14). For the line diffuser, there did appear to be an oxygen delivery threshold necessary to maintain these conditions. We found that, so long as the applied gas flow rate was maintained above 40 SCFM, bottom DO conditions were maintained, but SWI DO was depressed at lower rates. DO levels were observed to increase once higher flow rates were attained, in contrast to past observations at Newman Lake, which showed the cone system was not able to recover from anoxic conditions by increasing daily oxygenation rates. At this point, there is inconclusive evidence if one system is better than the other with regards to direct oxygenation of sediments.

Keeping with the "development of an operation manual" in mind, hypolimnetic aeration (HA) and oxygenation (HO) are often turned over to a client with general instructions related to the mechanical equipment, a strong encouragement to collect discrete depth water column data, and a guideline for seasonal operation. Aside from the mechanical operating instructions, oxygen remediation strategies, with regards to water quality response based operation, tends to fall in the hands of the client. If the client is a more data savvy group, with their own limnologists or lake managers, there tends to be a better chance to continue adequate data collection to enhance system operation and performance. On the other hand, if the client has little room either budgetary or man power to obtain water column data, systems are operated more as an ON/OFF basis, with little regard to actual performance in terms of accomplishing the oxygenation targets.

Conclusion

We may not ever have a complete operation manual for oxygenation systems because, unlike automobiles (or perhaps geodesic domes), lakes and reservoirs are not mass-produced with standardized configurations and parts. Each oxygenation project must take into account site-specific conditions of the water body and each lake or reservoir may not respond the same to similar oxygenation applications. Fortunately, as reported above, we now have a lot of powerful tools at hand to assist us in *designing* cost-effective and successful oxygenation projects. Costs vary widely depending on application goals and site-specific conditions. Given this, we include costs for a selection of applications in Table 1.

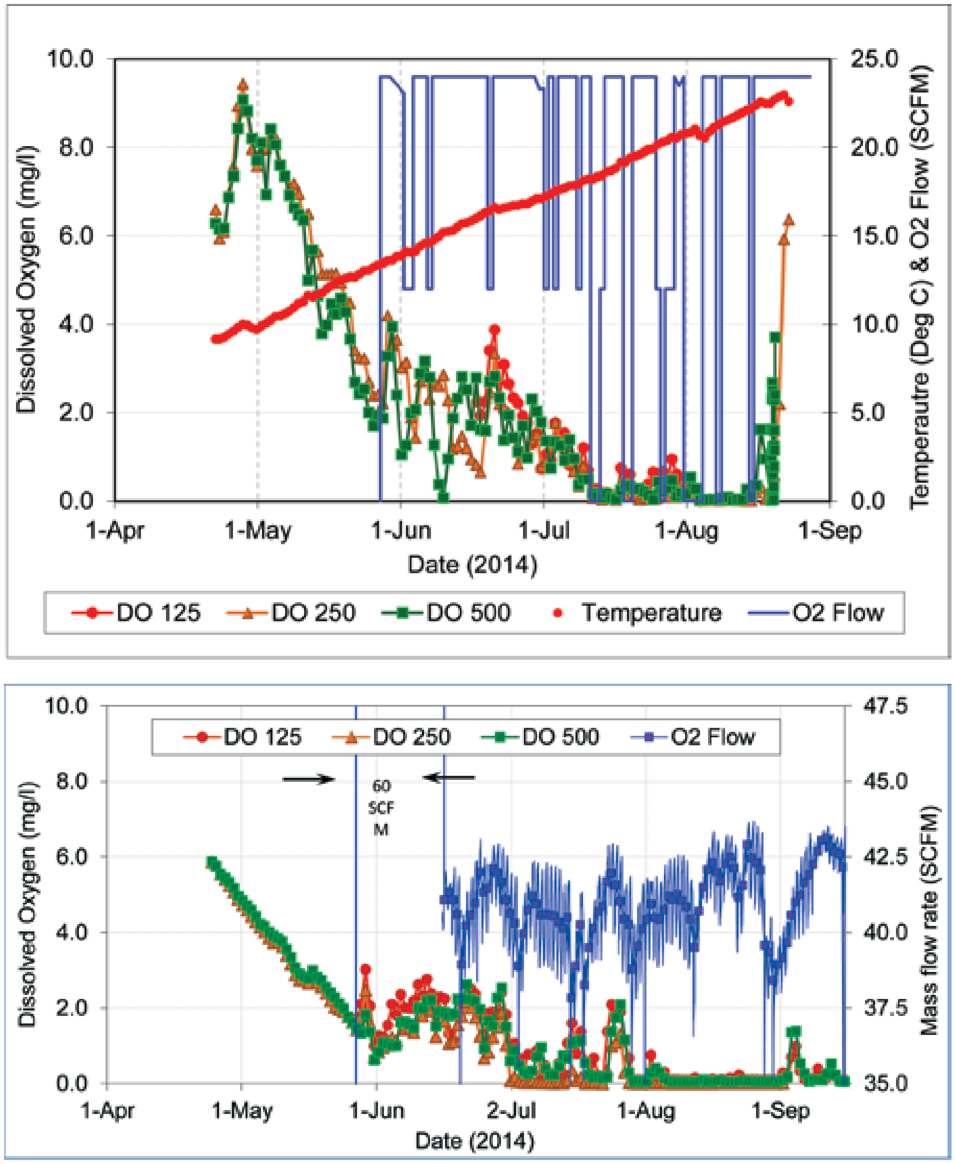


Figure 14, Oxygen content in Newman Lake (top) and North Twin Lake (bottom) during oxygenation from oxygen probes placed ~0.1 m (0.5 ft) above the bottom at 38, 76, and 152 m (125, 250, and 500 ft) distances from the HO apparatus showing positive oxygen content during system operation then decreasing when applied gas flow rates dropped or the system was shut down.

Research still needs to be done, especially on long-term, whole-lake ecological impacts of oxygenation, on better predictive tools for estimating total legacy oxygen demand, and on means to estimate anticipated longevity of oxygenation requirements. While total turnkey, ON/OFF, install-run-forget operation may not be possible, oxygenation clients should be strongly encouraged to include adequate post-installation monitoring, and to seek professional advice from limnologists and lake managers to "fine-tune" HO system performance. The additional costs of such advice are a sound investment to

Table 1. Capacities and Costs of Selected Installations

Reservoir	*Type*	*Application*	*Capacity/Cost*[1]
Camanche 7,700 ac	Speece Cone (1 unit)	Hydropower	9 tons O_2/day $1.8M; $108K OM/yr
Lakes Prince and Western Branch 2,231 ac	Airlift Aerators (25 units)	Water supply	Compressed Air $2.8M
Richard B. Russell 26,650 ac	Bubble Plume (10 x 1200 m)	Hydropower	200 tons O_2/day $1.6M; $2.4M OM/yr
Upper San Leandro 620 ac	Bubble Plume (2 x 730 m)	Water supply	9 tons O_2/day $450K; $108K OM/yr
Spring Hollow 158 ac	Bubble Plume (1 x 400 m)	Water supply	0.3 tons O_2/day $200K; $3.6K OM/yr
Carvin's Cove 800 ac	Bubble Plume (2 x 600 m)	Water supply	2 tons O_2/day $450K; $24K OM/yr
Brick Reservoir 110 ac, 50' max depth	Two Layer Aerators Two Diffuser Modules	Water supply	160 SCFM[2]; 32 MGD $197K, $20K OM/yr
Shenipsit Lake 530 ac, 70' max depth	Two Layer Aerators	Water supply, Fishery	240 SCFM[2]; 55 MGD $270K, $23K OM/yr

[1]Annual cost includes only liquid oxygen for oxygen systems, power and service for compressed air systems. Costs vary widely by application goal and site-specific conditions.

[2]SCFM = standard cubic feet per minute

Liquid oxygen costs ~ $100/ton

ensure that overall water quality goals are achieved. In short, there is a growing portfolio of excellent results obtained to date in oxygenation applications for hydropower, water supply, and fish habitat, and these technologies should continue to offer restoration options when oxygen replenishment is necessary. While watershed management is essential for controlling eutrophication, in-lake management methods, such as those discussed here for maintaining aerobic conditions, can help maintain assimilative capacity and ecological integrity. Effective long-term lake management involves the whole ecosystem, land and water.

Citations

Ashley, K.I., D.S. Mavinic and K.J. Hall. 2008. Oxygenation performance of a laboratory scale Speece cone hypolimnetic aerator: preliminary assessment *Can J Civil Eng*, 35:663-675.

Beutel, M., I. Hannoun, J. Pasek and K.B. Kavanagh. 2007. Evaluation of Hypolimnetic Oxygen Demand in a Large Eutrophic Raw Water Reservoir, San Vicente Reservoir, Calif., *J Env Eng*, 133(2): 130-138.

Bryant, L.D., H. Hsu-Kim, P.A. Gantzer and J.C. Little. 2011. Solving the problem at the source: Controlling Mn release at the sediment-water interface via hypolimnetic oxygenation. *Water Res*, 45:6381-6392.

Burris, V.L., D.F. McGinnis and J.C. Little. 2002. Predicting oxygen transfer and water flow rate in airlift aerators. *Water Res*, 36:4605-4615.

Crutchfield Jr., John U., Mark Mobley, Richard J. Ruane, Paul Gantzer, Jon Knight and Paul J. Wolff. 2012. Application of a Reservoir Oxygen Diffuser System to Meet Dissolved Oxygen Requirements at the Tillery Hydroelectric Plant, North Carolina, HydroVision 2012, Louisville, KY.

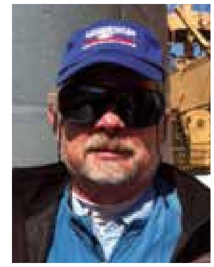
Davis, W.S., L.A. Fay and C.E. Herdendorf. 1987. Overview of USEPA/Clear Lake Erie Sediment Oxygen Demand Investigations during 1979, *J. Great Lakes Res*, 13(4):731-737.

Dent, S.R., M.W. Beutel, P. Gantzer and B.C. Moore. 2014. Response of methylmercury, total mercury, iron and manganese to oxygenation of an anoxic hypolimnion in North Twin Lake, Washington. *Lake Reserv Manage*, 30(2):119-130.

Funk, W.H. and B.C. Moore. 1988. Newman Lake restoration feasibility study. Final report. State of Washington Water Research Center. WRC Report No. 69. Pullman, WA.

Gantzer, P.A., L.D. Bryant and J.C. Little. 2009. Controlling soluble iron and

manganese in a water-supply reservoir using hypolimnetic oxygenation," *Water Res*, 43:1285-1294.
Gantzer, P.A., L.D. Bryant and J.C. Little. 2009. Effect of hypolimnetic oxygenation on oxygen depletion rates in two water-supply reservoirs. *Water Res*, 43:1700-1710.
Gerling, A.B., R.G. Browne, P.A. Gantzer, M. Mobley, J.C. Little and C.C. Carey. 2014. First report of the successful operation of a side stream supersaturation hypolimnetic oxygenation system in a eutrophic, shallow reservoir. *Water Res*, 67:129-143.
Kortmann, R.W. 1980. Benthic and atmospheric contributions to the nutrient budgets of a soft-water lake. *Limno. Ogr*, 25:229-33.
Kortmann, R.W. and P.H. Rich. 1994. Lake system energetics: The missing management link. *Lake Reserv Mgt*, 8(2):77-97.
Kortmann, R.W., G.W. Knoecklein amd C.H. Bonnell. 1994. Aeration of stratified lakes: Theory and practice. *Lake and Reserv Manage*, 8(2):99-120.
Lorenzen, M.W. and A.W. Fast. 1977. "A Guide to Aeration/Circulation Techniques for Lake Management." *Ecol Re Ser, EPA-600/3-77-004.* U.S. Environmental Protection Agency.
McGinnis, D.F., A. Lorke, A. Wüest, A. Stöckli and J.C. Little. 2004. Interaction between a Bubble Plume and the Near Field in a Stratified Lake. *Water Resources Res,* 40: W10206.
McGinnis, D.F. and J.C. Little. 2002. Predicting diffused-bubble oxygen transfer rate using the discrete-bubble model. *Water Res*, 36:4627-4635.
Mobley, Mark H., R. Jim Ruane and E. Dean Harshbarger. 2000. And Then It Sank...The Development of an Oxygen Diffuser for Hydropower, HydroVision 2000 Charlotte, North Carolina.
Mobley, Mark H. P.E., Paul Gantzer, Ph.D., P.E., Gary E. Hauser, P.E., Richard Jim Ruane and Jamie A. Sykes. 2012. Oxygen Diffuser System to Create Fish Habitat and Enhance Hydropower Water Quality in the J. Strom Thurmond Reservoir, HydroVision International 2012, Louisville, KY.
Moore, B.C., B.K. Cross, E.M. Clegg, B.P. Lanouette, M. Skinner, E.Preece, A. Child, P. Gantzer, E. Shallenberger, D. Christensen and B. Nine. 2014. Hypolimnetic oxygenation in Twin Lakes, WA, Part I: Distribution and movement of trout following hypolimnetic oxygenation in North Twin Lake, Washington. *Lake Reserv Manage*, 30(3):226-239.
Moore, B.C. and D. Christensen. 2009. Newman Lake restoration: A case study Part I: Chemical and biological responses to phosphorus control. *Lake Reserv Mgt*, 25(4):337-350.
Moore, B.C., A.C. Richter and D. Christensen. 2009. Newman Lake restoration: A case study Part II: Microfloc alum injection. *Lake Reserv Mgt,* Vol. 25(4):351-363.
Moore, B.C., B.K. Cross, M. Beutel, S. Dent, E. Preece and Mark Swanson. 2012. Newman Lake Restoration: A Case Study Part III: Hypolimnetic oxygenation. *Lake Reserv Manage*, 28(4):311-327.
Moore, B.C., P.H. Chen, W.H. Funk and D. Yonge. 1996. A model for predicting lake sediment oxygen demand following hypolimnetic aeration. *Water Resources Bull,* 32(4):723-731.
Murphy, P.J. and D.B. Hicks. 1985. In-situ Method for Measuring Sediment Oxygen Demand. In, Sediment Oxygen Demand, Processes, Modeling, and Measurement, Institute of Natural Resources, Athens, GA.
Nürnberg, G.K. 1995. Quantifying anoxia in lakes. *Limno Ogr*, 40(6):1100-1111.
Singleton, V.L. and J.C. Little. 2006. Designing hypolimnetic aeration and oxygenation systems – A Review. *Env. Sci Tech*, Vol. 40:7512-7520.
Singleton, V.L., P. Gantzer and J.C. Little. 2007. Linear bubble plume model for hypolimnetic oxygenation – Full-scale validation and sensitivity analysis. *Water Resources Res,* 43:W02405.
Singleton, V.L., F.J. Rueda and J.C. Little. 2010. A coupled bubble plume-reservoir model for hypolimnetic oxygenation. *Water Resources Res*, 46:W12538.
Skinner, M.M., B.C. Moore and M.E. Swanson. 2014. Hypolimnetic oxygenation in Twin Lakes, WA, Part II: Feeding ecology of a mixed cold and warm water fish community. *Lake Reserv Manage*, 30(3):240-249.



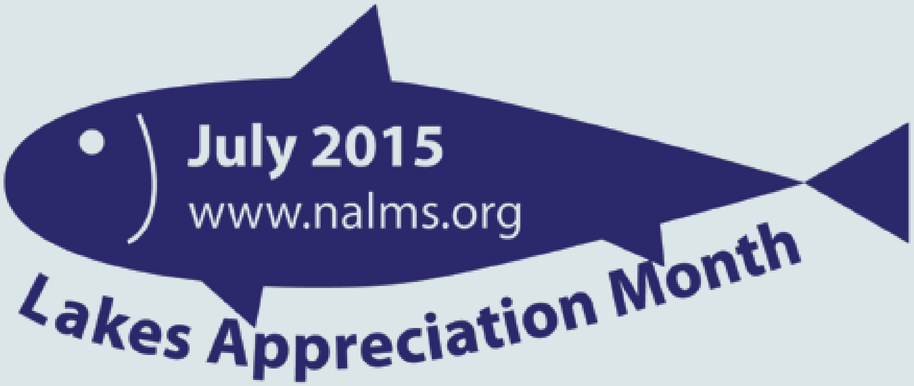
Dr. **Barry C. Moore** is an aquatic ecologist with particular interests in fate and effects of aquatic pollutants, such as nutrients and heavy metals, and on invasive species. His research centers on short and long term responses of lake ecosystems to management and restoration, and on evaluating efficacy of pollution abatement technologies, especially oxygenation. As a NAUI Scuba Instructor for 35 years, he has certified and introduced over 8,000 students to the underwater environments of marine and freshwater systems.

Mark Mobley, P.E., founded Mobley Engineering, Inc. in 1999 after 16 years with the Tennessee Valley Authority Engineering Laboratory. Mobley Engineering offers reservoir diffuser systems for hydropower, water supply, temperature control, and fish habitat. He has been responsible for the installation of over 40 reservoir diffusers systems using compressed air or oxygen. You can reach Mark at: mark@mobleyengineering.com.

John Little is the Charles E. Via Jr. Professor of Civil and Environmental Engineering at Virginia Tech. His current research interests include managing water quality in lakes and reservoirs (for example, controlling the release of phosphorus, iron and manganese from sediments using oxygenation, managing the growth of algae using in-situ mixing techniques, and evaluating the effect of climate change on water quality). John is currently chair of the International Water Association (IWA) Specialist Group on Lake and Reservoir Management.

Bob Kortmann is an applied "ecosystem limnologist" and a NALMS member since the beginning. For the past 40 years his work has dealt with physical, chemical, and biological interactions in lake and

(Moore et al., continued on page 68 . . .)



The month of July is Lakes Appreciation Month!

You work on them. Play on them. Drink from them.

But do you take time to really appreciate your local lake, pond, or reservoir?

Lakes Appreciation Month is a time to think about where you would be without water. It is also a time to think about the threats facing your lakes and reservoirs. Growing population, development, and invasive plants and animals put stress on these waterbodies. All life relies water. And as you know, we can no longer afford to take for granted that these water resources will always be there and always be usable.

Learn how you can help NALMS make the most out of Lakes Appreciation Month. See our website for details on the following:

- You can sign a letter to U.S. governors asking that they proclaim July as lakes appreciation month in your State.
- You can pursue media coverage for your local Lakes Appreciation events.
- You can join the Secchi Dip-In and help track water quality trends in your local lake or reservoir.
- You can help promote Lakes Appreciation by sharing your experiences through our "Show You Lakes Appreciation Challenge."

Lakes Appreciation Month is also a good time to set aside a week, a day, or even just an hour to celebrate your favorite waterbody. Here are some more ideas:

- You can help monitor your local waterbody or watershed
- You can visit a local lake, pond, or reservoir with friends and family
- You can go boating, kayaking, canoeing, sailing, or rowing
- You can go swimming
- You can go SCUBA diving
- You can cast your line in and go fishing
- If you manage a lake you can host an activity in your office or on a local waterbody. Bring enough sampling gear, id keys and other materials for everyone to join in.
- If you don't manage a lake, you ask your local lake agency about shadowing a lake manager for a day
- You can arrange a lake or watershed clean-up event
- You can start a watershed storm drain stenciling program
- You can have your septic system pumped if you live close to a waterbody
- You can go birding or take pictures at a lake or pond
- You can tap into your artistic side and draw or paint a lake scene for your home or office. Be sure to send us a copy!
- You can organize a lake field trip for students

(. . . Moore et al., continued from page 29)

watershed ecosystems, and innovative management technologies. He founded Ecosystem Consulting Service, Inc. in 1979, and has worked on projects coast-to-coast and as far away as Sao Paulo, Brazil.

Paul Gantzer graduated from Virginia Tech in 2008 with a Ph.D. working under the guidance of John Little. He started Gantzer Water Resources Engineering the same year, focusing on lake and reservoir monitoring and management, specifically related to oxygenation and aeration. Over the past 15 years, Paul has worked on projects across the U.S. with Mark Mobley and, in recent years, with Bob Kortmann and Barry Moore.

Next Issue – Summer 2015 *LakeLine*

As has been our recent custom every other year, the summer issue of LakeLine will feature Harmful Algal Blooms (HABs). It will feature U.S. EPA activities, including EPA's HAB awareness campaign, citizen monitoring and mobile App technologies, satellite monitoring, HAB drinking water regulations and treatment technologies, and more.