

Evaluating the “Gradual Entrainment Lake Inverter” (GELI) artificial mixing technology for lake and reservoir management

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ABSTRACT

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Thermal stratification is important to the structure and function of lake and reservoir ecosystems. Yet when lakes undergo eutrophication, thermal stratification can exacerbate water quality problems. As a result, lake management has sometimes involved artificial mixing and destratification, though the available technologies are few and costly. It is therefore important to test the efficacy of new technologies when they arise. Here, we evaluate a lake mixing technology, the “Gradual Entrainment Lake Inverter” (GELI), which was used to mix Crystal Lake, Wisconsin, a 34 ha, 21 m deep, dimictic lake during the summer months of 2012 and 2013. To assess the effect of the GELI treatment on thermal regime, we used DYRESM to model thermal conditions in the 2 treatment years but in the absence of treatment. We found GELI treatment slowly reduced stratification and the temperature range of the lake to 4.2 and 5.3 C in each treatment year, on average. Full destratification and oxygenation of the water column prevented fall hypoxia and anoxia. We found efficiency of the GELI averaged 1.9% during treatment, which is higher than efficiencies reported from field applications of bubble plume aeration. We used DYRESM to simulate bubble plume aeration to match the observed destratification from our GELI treatment and estimate aeration would have required 1.4–1.8 times the airflow and power costs of the GELI. Though considerable limitations of the current iteration of this technology exist, these may be reduced in future versions, possibly leading to a practical lake and reservoir management tool.

KEYWORDS

Aeration; destratification; physical controls; technology; water quality

The seasonal warming of lake surface waters and insufficient wind-driven mixing leads to the partitioning of the water column into disconnected layers (Birge 1916). This process of thermal stratification is important to the timing of seasonal production (Sverdrup 1953) and in many ways determines the structure and function of aquatic ecosystems (Wetzel 2001). Stratified systems experiencing eutrophication can result in hypolimnetic anoxia and resultant internal loading of nutrients and mobilization of other elements that can have harmful effects (Pastorok et al. 1982, Postel and Carpenter 1997). An in-lake solution to the problem of internal loading is artificial mixing in which turbulence is enhanced and stratification is reduced. Artificial mixing reduces hypolimnetic isolation from the lake surface leading to a well-oxygenated water column.

Through this primary mechanism of reoxygenation, artificial mixing has been useful in addressing the

internal loading of nuisance chemicals (Symons et al. 1967, Pastorok et al. 1982), preventing fish kills and expanding the habitat of warm water fish species (Fast 1968, Halsey 1968, Ferraris and Wilhm 1977), and oxidizing cyanide by-products in mine pit lake restoration (Pieters et al. 2015); it also has the potential to decrease methylmercury bioaccumulation (Perron et al. 2014). Artificial mixing increases the heat and nutrient flux between thermal layers leading to its efficacy in reducing cold-water discharge from impounded waters (Miles and West 2011), and stimulating primary and secondary production leading to increased aquaculture yields (Strohmeier et al. 2015). Furthermore, artificial mixing has been used as an experimental tool to control aquatic invasive species (Gaeta et al. 2012, Lawson et al. 2015), evaluate the role of thermal regime in structuring lake ecosystems (Shade et al. 2012), reduce evaporation from reservoirs (Helfer et al. 2011), and simulate

impacts of lake warming due to climate change (Lydersen et al. 2008, Sastri et al. 2014).

The many uses and benefits of mixing come with the price of the selected technology. Of the available technologies for artificial destratification (Wuest et al. 1992, Stephens and Imberger 1993, Kirke and Gezawy 1997), bubble plume aeration is favored because of its mechanical simplicity and modest maintenance costs (Klapper 2003). This method releases compressed air through a perforated diffuser from which air bubbles rise to the lake surface while carrying water upward in a turbulent plume. At the lake surface this water exits the plume at a lower density than originally entrained, yet greater than the surrounding water, and it falls to the depth of equivalent density where it flows horizontally away from the plume. Continuation of this process reduces the vertical density gradient of the water body until stratification is eliminated. Rather than using air bubbles to mix the lake, Read et al. (2011b) presented a novel lake mixing technology that used air to regulate the buoyancy of a device called a “Gradual Entrainment Lake Inverter” (GELI) that rose and fell in the water column, thereby imparting turbulent mixing to the lake. Their experimental use of the GELI to reduce stratification in North Sparkling Bog, Wisconsin, required an estimated 10 times less airflow than had they used bubble plume aeration. If these operational savings can be maintained as the GELI is applied to larger lakes, while simultaneously improving hypolimnetic oxygen content, then this technology may emerge as a practical lake and reservoir management tool.

Here, we report our application of this technology to destratify Crystal Lake, Wisconsin, which is 70 times larger in surface area and 350 times larger in volume than North Sparkling Bog. We predicted that the GELI would gradually decrease whole lake water temperature range until complete destratification was achieved and late season oxygen deficiencies prevented. According to Read et al. (2011b), we expected that the GELI would have a higher efficiency and substantially lower airflow requirements than bubble plume aeration. In addition, we highlight unique aspects of the GELI relevant to lake and reservoir management, critique its limitations, and provide recommendations for development of this technology.

Study site

Crystal Lake, Wisconsin (46°00′07″N, 89°36′37″W), is a dimictic, oligotrophic seepage lake, with no inlet

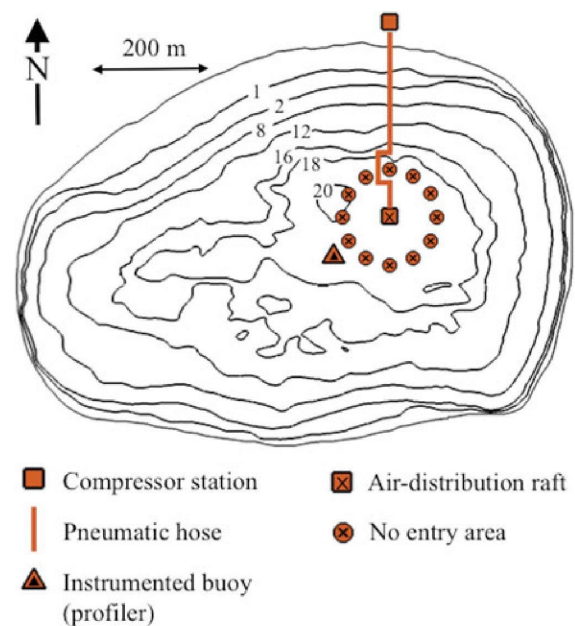


Figure 1. Crystal Lake bathymetry and locations of experimental equipment. Isobaths are in meters.

or outlet, and minimal groundwater inputs (Fig. 1). The lake is ice covered in winter and develops strong thermal stratification in summer. In fall the lake experiences reduced dissolved oxygen concentrations near the maximum depth of the lake but not widespread anoxia that is common to most stratified eutrophic lakes. During our study, Crystal Lake had an average surface area of 34 ha, maximum depth of 21 m, and volume of $3.7 \times 10^6 \text{ m}^3$. It had an average ice-free light attenuation coefficient of 0.28/m, Secchi depth of 7.1 m, and peak Schmidt stability of 626 J/m² in untreated years (2011 and 2014). The lake is a primary study site of the North Temperate Lakes Long Term Ecological Research program (Magnuson et al. 2006) and is a popular beach and campground that hosts ~125,000 visitors annually. We treated Crystal Lake in 2012 and 2013 with the GELI, while 2011 and 2014 are used as untreated years in this study.

Methods

Data collection and processing

We monitored limnological and meteorological variables during all years of our study (2011–2014). In Crystal Lake, we measured water temperatures and dissolved oxygen using a profiling buoy (a custom buoy that lowered a Hach DSX-5, $\pm 0.10 \text{ }^\circ\text{C}$, $\pm 0.1 \text{ mg/L}$, from 1 to 18 m at 1 m intervals every 6 h; Fig. 1)

and obtained fortnightly estimates of PAR light attenuation coefficient (K_d) from manual profiles taken at the buoy (Biospherical PUV-2500, 1 cm vertical resolution). We measured air temperatures and relative humidity (Campbell Scientific CS215) and wind speed (RM Young 05103) at the Crystal Lake buoy, and measured shortwave radiation (Eppley PSP pyranometer), longwave radiation (Eppley PIR radiometer), and precipitation (tipping bucket) at an airport station 13 km southwest of the lake (Noble F. Lee Memorial Airport, 45°55'40"N, 89°43'54"W).

After data collection, we filled gaps in the meteorological and water temperature time series, then resampled these data for modeling and analysis. We filled gaps in shortwave radiation using the method of Britton and Dodd (1976) and PAR measurements collected at a nearby lake (7 km west of Crystal Lake; LI-COR LI-190R). We filled gaps in longwave radiation using the method of Crawford and Duchon (1999). We filled gaps in other meteorological variables with averages spanning 1 week before and 1 week after a gap. We filled gaps in water temperature with linear interpolation (for use in figures but not in analyses). All meteorological data were downsampled to 1 h averages for use in hydrodynamic modeling. Model results were output at 6 h intervals to match Crystal Lake profiling and averaged to obtain daily values.

GELI technology overview

The GELI is a large flat disk that moves vertically through the water column (Fig. 2). While ascending, turbulence is generated through drag and a portion of

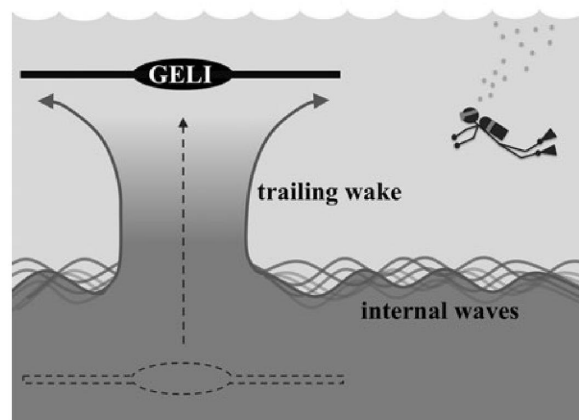


Figure 2. The cross-section of a stratified lake with a GELI moving vertically from the hypolimnion into the epilimnion.

cold hypolimnetic water is lifted into the epilimnion. While descending, warm epilimnetic water is carried downward into the hypolimnion. Read et al. (2011a) also observed internal waves from the GELI disturbance as a likely additional source of mixing. The GELI is constructed of a rugged geomembrane (XR-5 8130) stretched over and fastened to a stainless steel frame (8 m diameter) and has a centralized airbladder. Volumetric changes of the airbladder control buoyancy, which in turn drive vertical movement of the GELI through the water column.

A pneumatic system delivers compressed air to the GELI airbladder (Fig. 3). A shore-based compressor (2 HP, 1.5 kW; GAST 8HDM-19-M850X) feeds the floating air-distribution raft located on the lake. Air distribution at the raft is governed by a logic controller (Schneider Electric SR2) that iterates through 3 phases in the cycling of a single GELI. In phase 1, system pressure is increased above ambient pressure of the inactive

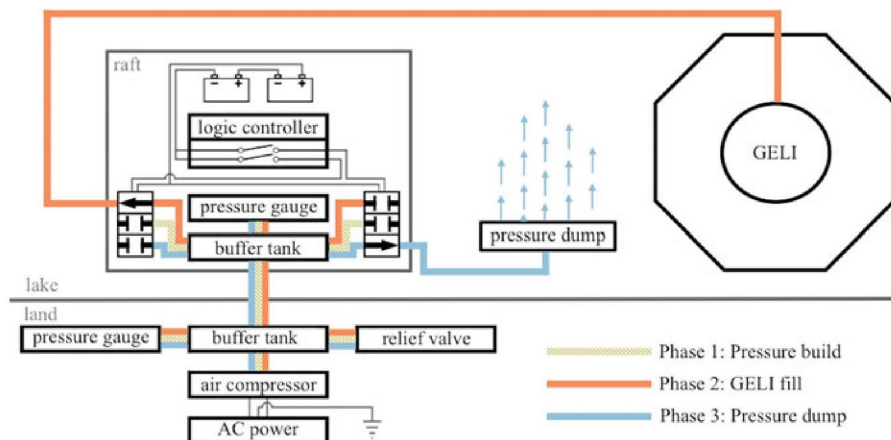


Figure 3. Pneumatic system of the GELI lake mixing technology.

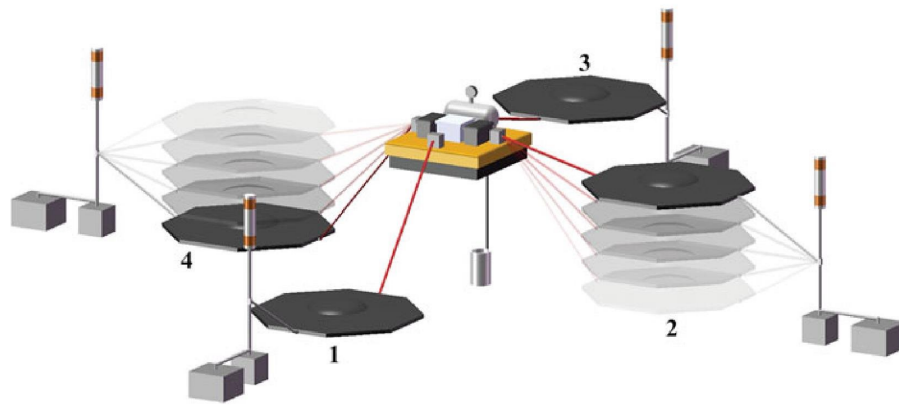


Figure 4. A bird's-eye view of a 4-GELI system, similar to the 6-GELI system used in our study. GELI-1 is negatively buoyant and on the lakebed. GELI-2 is inflated and ascending. GELI-3 is floating at the lake surface and venting. GELI-4 is negatively buoyant and sinking. Below the raft is the pressure release valve.

GELI resting on the lakebed so that in phase 2, when the GELI valve is opened (SMC VFS6000), the airbladder is inflated and the GELI ascends to the lake surface. In phase 3, excess system pressure is released until equilibration. This third phase is necessary because the controller does not detect system pressure. Rather it operates on timers that are calibrated to pressure building rates and airflows within the system. Once the GELI has reached the surface, it floats for a short period of time, venting air, before buoyancy is insufficient and it sinks back to the lakebed. After all individual GELI have been cycled (6 were used in this study), the system controller is reset and the process repeats.

To constrain the horizontal movements of the GELI, a 2-point mooring was used. Each GELI is anchored to an outer perimeter of concrete blocks (110 kg weight in water) with wire cable, and to the centralized raft with pneumatic hose (Fig. 4). The blocks provide the majority of anchoring strength while the raft provides a centralized tensioning point. In 2012 and 2013, we deployed the GELI, raft, and anchors at the deepest area of Crystal Lake (>18 m depth) and ran the system continuously from April/May until mid-September when the lake was consistently losing heat and isothermal conditions were sustained.

Evaluating GELI treatment

Two ways can be used to express the effect of the GELI treatment on the thermal regime relative to untreated conditions. One is to use the 2 untreated years (2011 and 2014) as reference conditions. The other is to simulate the thermal regime in the treatment years, but in the absence of GELI treatment.

We opted for the latter option because among-year variation in meteorological forcing can dramatically affect events such as ice-off date and onset of thermal stratification (e.g., Crystal Lake ice-off: 20 Mar 2012 and 7 May 2013). Since hydrodynamic models such as the Dynamic Reservoir Simulation Model (DYRESM; Imberger and Patterson 1981) are effective at modeling thermal stratification from meteorological conditions, this approach provides a better reference state than untreated years (2011 and 2014).

We used DYRESM v. 3.0 (Antenucci and Imerito 2003) to model what the thermal regime of Crystal Lake should have been in the absence of treatment. DYRESM is a one-dimensional hydrodynamic model suitable for simulating the thermal regime of small to medium sized lakes with simple morphometry. Inputs to the model include atmospheric conditions (shortwave radiation, longwave radiation, wind speed, vapor pressure, and precipitation), inflows, outflows, and lake-specific parameters, such as hypsography, water clarity, and initial water temperatures. Outputs from the model include water temperature profiles at a user-specified frequency. We parameterized DYRESM with physical constants derived from process studies and data from Crystal Lake (Table 1). The light attenuation coefficient was input as the mean of ice-free K_d estimates of untreated years (2011 and 2014). Initial water temperatures were input as the first profile where the temperature range, measured at 1 and 18 m from the surface, was 1.5–2.0 °C. These conditions are typically met within 2 weeks of ice-off. We did not input groundwater inflows and outflows to the model since it is a minor contribution to the water budget (approximately 5%; Kenoyer and Anderson 1989).

Table 1. List of parameters supplied to DYRESM for modeling untreated conditions and aeration treatment.

Parameter	Value	Source
Bulk aerodynamic momentum transport	1.4×10^{-3}	Stull (1988)
Albedo of water	0.08	Patten et al. (1975)
Emissivity of water surface	0.96	Imberger and Patterson (1981)
Critical wind speed	3.0	Spigel et al. (1986)
Bubble coefficient	6.0×10^{-3}	Antenucci and Imerito (2003)
Entrainment coefficient	8.3×10^{-2}	Fischer et al. (1979)
Number of plume sources	30	Schladow (1993)
Shear production efficiency	0.08	Christodoulou (1986)
Potential energy-mixing efficiency	0.20	Spigel et al. (1986)
Wind-stirring efficiency	0.4	Spigel et al. (1986)
Light attenuation coefficient (untreated)	0.28	Field data (mean of 2011 and 2014)
Light attenuation coefficient (treated)	0.36/0.39	Field data (2012/2013)
Effective surface area coefficient	1.0×10^7	Yeates and Imberger (2003)
Benthic boundary layer mixing	1.0×10^{-5}	Yeates and Imberger (2003)
Vertical mixing coefficient	200	Yeates and Imberger (2003)
Minimum/maximum layer thickness	0.05/0.25	Calibrated

and energy budget. We then calibrated the model by adjusting minimum and maximum layer thicknesses until differences between the modeled and observed thermal regime were minimized.

We validated DYRESM simulations for the untreated years (2011 and 2014) by comparing modeled and observed lake stratification indices: water temperatures at 1 and 18 m, depth to top and bottom of the metalimnion, depth of the thermocline, and Schmidt stability. These indices describe fundamental lake stratification characteristics and were calculated with the LakeAnalyzer software package (Read et al. 2011a). We then calculated the root mean square error (RMSE) between modeled and observed indices and percent RMSE by dividing by the observed range (2011 and 2014; Table 2).

Having validated simulations of 2011 and 2014, we used DYRESM to simulate what the untreated thermal regime would have been in 2012 and 2013. The effect of the GELI treatment was evaluated by comparing lake temperature range of observed and modeled untreated conditions.

Table 2. Root mean square error (RMSE) and percent RMSE (in parenthesis) between modeled and observed lake stratification indices for untreated years of Crystal Lake (2011, $n = 202$; 2014, $n = 193$). RMSE was calculated at daily time steps for the full open water period of these years.

Variable	2011	2014
Temperature at 1 m (C)	0.91 (4.5)	0.75 (4.1)
Temperature at 18 m (C)	0.57 (11)	0.20 (5.1)
Metalimnion top (m)	1.3 (7.4)	0.86 (5.1)
Metalimnion bottom (m)	1.1 (6.6)	1.1 (6.5)
Thermocline (m)	1.2 (7.6)	1.0 (6.1)
Schmidt stability (J/m ²)	32 (4.7)	26 (4.6)

Dissolved oxygen

We assessed the effect of GELI treatment on dissolved oxygen of Crystal Lake in 2 ways. First, we combined lake hypsography with oxygen profiles to compute average volumetric proportion of the lake occupied by hypoxic water (<2 mg/L) during treatment and nontreatment years. Second, we tracked the presence of anoxic water near the sediment–water interface via the 18 m depth time series from the dissolved oxygen profiles.

Technology comparison

We compared the GELI efficiency to that of common bubble plume aeration using 2 methods. First, we calculated mechanical efficiency of the GELI and compared it to published values for aeration; second, we used the DYRESM bubble plume subroutine to estimate the total free airflow required by aeration to produce the same amount of destratification that was observed during GELI treatment.

Mechanical efficiency is a measure of the amount of destratification per unit energy input by the lake mixing technology. This provides a metric of destratification effectiveness irrespective of whether the technology is a bubble plume or a GELI. We calculated mechanical efficiency according to Schladow (1993):

$$\eta_{\text{mech}} = \frac{\Delta PE}{W_{\text{iso}}} \quad (1)$$

where ΔPE is the change in potential energy of the water column over a time step and W_{iso} is the isothermal work of compression defined as:

$$W_{\text{iso}} = 2.303 P_a Q_T \Delta t \log \frac{P_h}{P_a} \quad (2)$$

where P_a is the absolute pressures at the lake surface, Q_T is the total free airflow rate of the compressor, Δt is the time step over which the air compressor operates, and P_h is the absolute pressure at the lake bed. Total free airflow of the GELI was not measured; rather, it was estimated as a function of observed internal system pressure combined with the manufacturer-specified relationship between free airflow and working pressure. We observed changes in system pressure throughout the 3 phases of the GELI cycle at second resolution and converted these pressures to free airflow given manufacturer specifications, and then we averaged airflows over the cycle to get an estimate of free airflow for the GELI. We calculated potential energy from lake hypsography and water temperature profiles as

$$PE = g \sum_{i=1}^n \rho_i A_i (z_i - z_{cv}) \partial z_i \quad (3)$$

where g is the acceleration due to gravity, ρ_i is the density of layer i , A_i is the area of layer i , z_i is the depth to the midpoint of layer i , z_{cv} is the depth to the center of volume of the lake, and ∂z_i is the thickness of layer i . Because significant changes to PE can occur from natural meteorological processes (e.g., wind-induced mixing and convective cooling), we calculated PE as the difference between PE_{modeled} and PE_{observed} . We calculated mechanical efficiency between consecutive daily averaged water temperature profiles during the treatment periods of 2012 and 2013.

In addition to comparisons of efficiency, we used the DYRESM destratification subroutine to estimate the airflow required by aeration to mix Crystal Lake to the same extent achieved by the GELI. We constrained aeration to match the GELI destratification to facilitate comparison of airflow requirements and costs of these 2 technologies. The DYRESM subroutine is based on simple plume equations of conservation of mass, volume, and momentum, and assumes that the plumes are one-dimensional and noninteracting (Patterson and Imberger 1989). This approach has been successful in predicting the effects of aeration on lake stratification (Patterson and Imberger 1989, Schladow 1993, Schladow and Fisher 1995). We calculated the number of plume sources required to dismantle peak mid-summer thermal stratification at Crystal Lake in an 8 d period using the bubble plume design methodology of Schladow (1993), and parameterized DYRESM aeration with the resulting 30 plume sources. Light

attenuation was input as mean ice-free K_d estimates observed during GELI treatment, and aeration was set to run over the same period the GELI was in operation in each treatment year (2012 and 2013). We assumed the same amount of destratification with aeration would produce a similar biogeochemical response and concomitant change in K_d as observed during GELI mixing.

Once these parameters were finalized, we ran DYRESM aeration through a series of airflows (0–15 L/s, by 0.5 L/s increments). We considered the best match to be the airflow that minimized the RMSE between the modeled aeration and observed GELI temperature range. The simulations were run separately for 2012 and 2013, allowing us to estimate aeration required to match the destratification from the GELI system in each treatment year, and thus compare the operational requirements of these 2 technologies.

Results

GELI treatment

GELIs were cycled approximately 54,000 and 51,000 times in Crystal Lake in 2012 and 2013, respectively. In 2012 the GELI system ran on 1 compressor (3.8 L/sec) for 150 d, and in 2013 ran on 1 compressor for 78 d and 2 compressors for 42 d (5.1 L/sec mean flow rate).

GELI treatment produced hypolimnetic warming and growth of the epilimnion with respect to the modeled untreated conditions (Fig. 5A–D). This resulted in a steady reduction in the temperature range of Crystal Lake with respect to the untreated reference conditions (Fig. 5E–F). Observed Crystal Lake surface water temperatures closely followed the seasonal trends and daily fluctuations of modeled untreated temperatures (Fig. 5E–F). Bottom water warmed 0.8 and 0.9 C/week faster than modeled temperatures of 2012 and 2013, respectively (Fig. 5E–F) and led to an average temperature range of 5.3 and 4.2 C throughout the summer period in 2012 and 2013, respectively. By mid-September, bottom water temperatures reached maxima of 21.0 and 20.8 C, which were 13.8 and 14.9 C higher than modeled temperatures of 2012 and 2013, respectively. After these peaks in temperature, Crystal Lake began losing heat and sustained isothermal conditions approximately 1.5 mo earlier than the modeled untreated references.

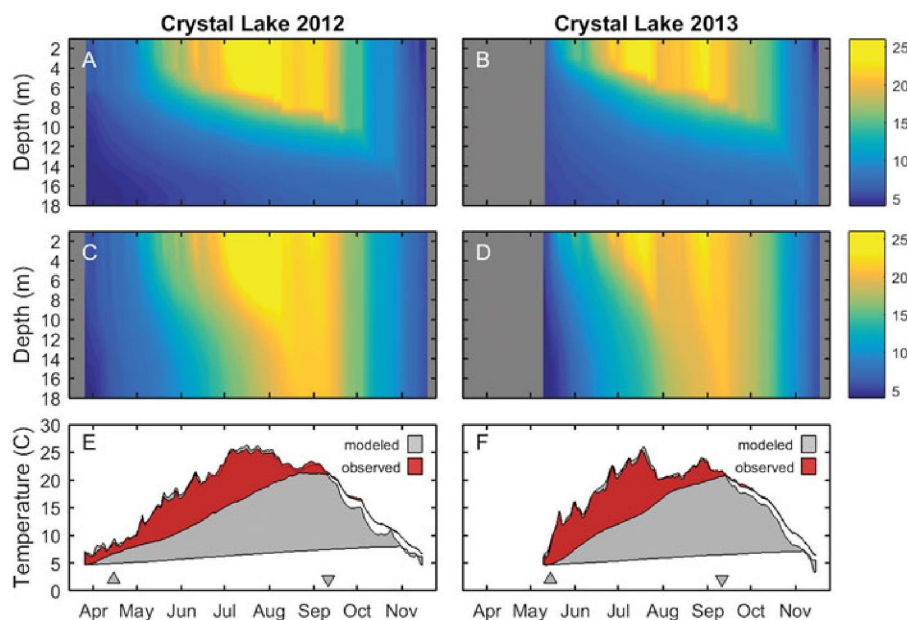


Figure 5. Crystal Lake water temperature profiles of simulated untreated conditions (A–B), and observed during GELI treatment (C–D). Color bar indicates water temperatures in degrees C. Daily temperature range (E–F) for modeled untreated conditions (gray) overlaid with observations from GELI treatment (red). Triangles denote the beginning (up pointing) and end (down pointing) of GELI treatment.

These earlier isothermal conditions of treatment years reoxygenated the water column and prevented fall anoxia of nontreatment years 2011 and 2014 (Fig. 6). Though dissolved oxygen at 18 m declined 0.1–0.2 mg/L/week faster in treatment years than nontreatment years, sustained anoxia in October was prevented (Fig. 6). On days when hypoxia was present, the average proportion of Crystal Lake experiencing hypoxia was approximately 60% less in treatment years 2012 (0.08) and 2013 (0.06) than in nontreatment years 2011 (0.14) and 2014 (0.29).

In these treatment years, mechanical efficiency of the GELI varied with highs coinciding with periods of greatest stratification and lows occurring with weak stratification or periods of strong natural mixing (Fig. 7A–B). A large percentage of days (2012: 38%;

2013: 31%) were dominated by natural sources of mixing. Efficiency averaged 1.9% in 2012 and 2013.

Modeled aeration treatment

DYRESM aeration reproduced the temperature range observed during GELI treatment with reasonable accuracy. The temperature range of 2012 was reproduced with 30 plumes and a total free airflow rate of 5.5 L/sec (RMSE = 1.4 C, percent RMSE = 15%, $n = 150$; Fig. 7C). The temperature range of 2013 was reproduced with 30 plumes and a total free airflow rate of 9.0 L/sec (RMSE = 0.8 C, percent RMSE = 7.1%, $n = 120$; Fig. 7D).

Overall, DYRESM aeration reproduced the large-scale seasonal changes and daily fluctuations in temperature range but with notable differences. Modeled surface and bottom water temperatures were cooler than observed with surface temperatures having greater daily oscillation (Fig. 7E–F).

Discussion

In this study, we applied the novel GELI lake mixing technology to destratify Crystal Lake, Wisconsin, a lake that is 2 orders of magnitude larger than had been previously treated with an earlier version of the GELI (Read et al. 2011b). We began treatment at the onset of thermal stratification and ended

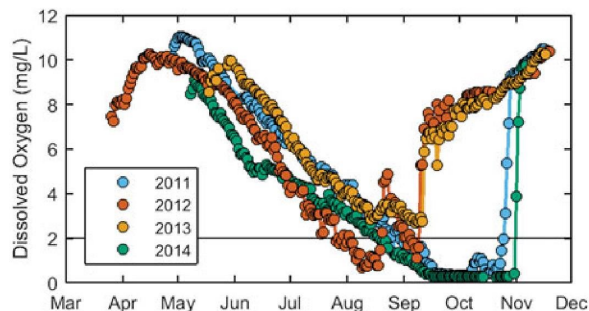


Figure 6. Crystal Lake daily dissolved oxygen at 18 m depth for the open water period of untreated years (2011 and 2014) and treatment years (2012 and 2013). Hypoxia is delineated at 2 mg/L.

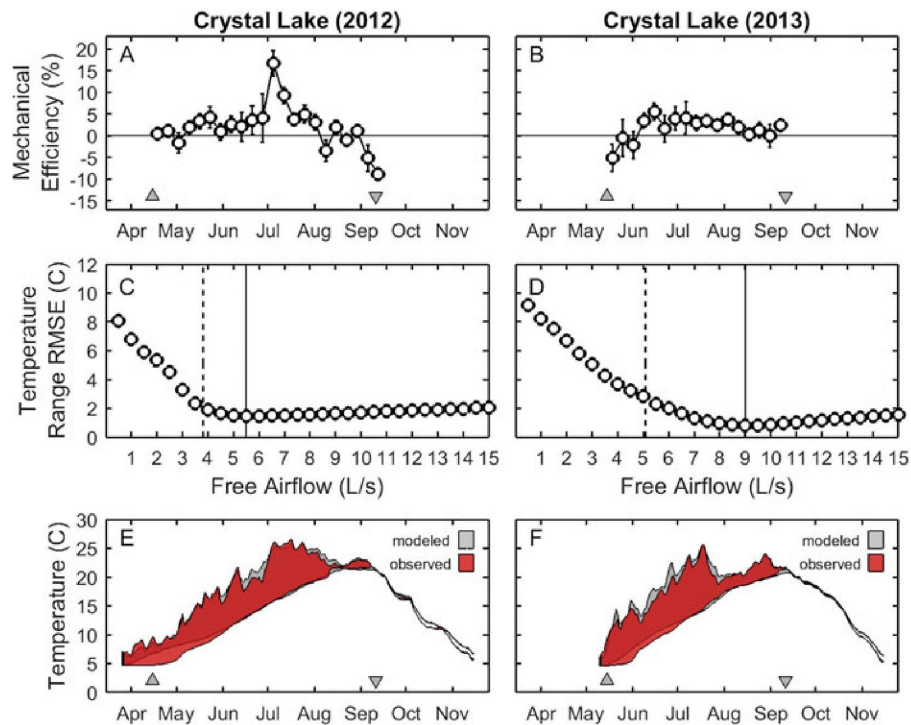


Figure 7. Weekly averaged mechanical efficiency estimates of the GELI during treatment (A–B). Error bars denote standard error. DYRESM aeration optimization curves during treatment years (C–D). GELI and aeration airflow requirements are denoted with vertical dashed and solid lines, respectively. Crystal Lake daily temperature range (E–F) observed during GELI treatment (gray) overlaid with the temperature range resulting from DYRESM modeled aeration (red). Triangles denote the beginning (up pointing) and end (down pointing) of GELI treatment and modeled aeration treatment.

treatment once isothermal conditions were sustained. During this 4–5 mo period of each treatment year, the temperature range gradually decreased relative to modeled untreated conditions. Bottom water temperatures warmed at accelerated rates leading to an early turnover and sustained isothermal conditions. This destratification decreased late-summer hypoxia and completely averted the fall anoxia of untreated years. This improvement in water quality was accomplished at greater efficiencies than field applications of bubble plume aeration reported by Bernhardt (1967; 0.47%), Symons et al. (1967; 0.1–1.5%), Patterson and Imberger (1989; 1.5%), and Pieters et al. (2015; 1.0%). Had we removed the pressure equilibration phase of the GELI cycle, in which excess system pressure is released (i.e., wasted power), then we estimate a 25% reduction in compressor run time and improved efficiencies of 2.6% for 2012 and 2013. These GELI efficiency estimates are considerable improvements over reported field applications yet fall short of idealized aeration for Crystal Lake (Schladow 1993; 8.9% for 2012 and 8.5% for 2013) and complex control strategies of simulated aeration presented by Sahoo and Luketina (2006; 3.7%) and Patterson and Imberger (1989; 15%). Our DYRESM

aeration simulations showed a similar amount of destratification would have required aeration 1.4–1.8 times the airflow required by the GELI in 2012 and 2013, respectively (1.9–2.3 times with elimination of the GELI pressure equilibration phase). These results suggest our application of the GELI in Crystal Lake was nearly as efficient as reported in the original case study by Read et al. (2011b); however, the airflow requirements of the GELI were not appreciably less than had we used bubble plume aeration. We discuss potential reasons for this below.

When selecting an approach to lake restoration it is not enough to consider technological efficiency. One must also consider process efficiency, the efficiency by which a technology improves the impaired state. In our instance the impairment is late-summer hypoxia and fall anoxia, an impairment which the slow destratification produced by the GELI was capable of averting; however, if the impairment was severe hypolimnetic oxygen losses within weeks to a month after the onset of stratification, an impairment common in eutrophic lakes, then the GELI would have failed markedly. In such a scenario, hypolimnetic warming would exacerbate internal loading processes thereby creating

additional burdens on water quality treatment (Cooke and Carlson 1989) and could effectively act as a nutrient pump resulting in cyanobacterial blooms and a further deterioration of water quality (Symons et al. 1967, Pastorok et al. 1982, Postel and Carpenter 1997, Ibelings et al. 2014). To expand the mixing capacity of the GELI system, we could have rearranged the moorings to accommodate additional GELI devices, which would have involved considerably more effort in contrast to simply increasing airflow rates and adding plume sources under the bubble plume aeration scenario. Though slow mixing has its limitations, there is an important cost tradeoff with the energetically intensive fast mixing approach that may not be necessary in all water quality remediation scenarios. We found the slow mixing of the GELI to be a suitable option for improving the late-season hypolimnetic oxygen deficit of Crystal Lake. Further testing and development will be required to understand sizing guidelines and to increase the mixing effectiveness of the GELI.

In addition to mechanical and process efficiency, other aspects of the GELI relevant to lake and reservoir management should be considered. First, the GELI requires an exclusion area to keep lake users from hazard. At Crystal Lake, this represented approximately 5% of the lake surface area. We estimate this to be an equivalent area required by our DYRESM simulated aeration system composed of 30 noninteracting plumes (Asada and Imberger 1993). Second, we found no evidence for impacts of the GELI mixing system on the lake biota, though it is possible that there could be impacts. For example, zooplankton could be transported through the water column because of GELI mixing. It would seem unlikely that fish would be abducted to the lake surface by a slowly ascending GELI (~ 10 cm/sec) but it is possible that fish could be affected by a rapidly descending GELI device. Third, the mixing mechanisms of the GELI result in a growing of the epilimnion and shrinking of the hypolimnion, which is the opposite of what occurs during destratification via bubble plume aeration. This translates to a greater water column stability with use of the GELI, which lessens the contribution of natural sources of mixing to achieving destratification of the lake (Schladow 1993, Schladow and Fisher 1995); however, a growing epilimnion under GELI treatment results in a larger proportion of the lake being reoxygenated from contact with the lake surface. Finally, from our estimates, the airflow

requirements of the GELI are less than bubble plume aeration. Thus, problems associated with nitrogen supersaturation (Westgard 1964, Fast and Hulquist 1982, Pastorok et al. 1982) will be reduced; however, the benefits of increased oxygen dissolution that come with aeration would also be reduced.

Once the range of water quality remediation tools have been narrowed to a set of viable options, then considerations of cost become important. The capital cost of the Crystal Lake GELI system was \$53,000, and includes all materials consumed in the initial construction phase and deployment. In terms of power costs (i.e., free airflow requirements divided by the airflow rate of a single compressor, multiplied by the operational period, multiplied by the cost per kWh), the combined cost of treating Crystal Lake in 2012 and 2013 with the GELI was \$3000. The costs of an aeration system capable of matching the destratification achieved with the GELI, based on our DYRESM simulations, would be \$46,000 and \$5000 for capital and power costs, respectively. Since capital costs of the GELI are \$7000 more than aeration, and operational costs save \$1000/yr, it would take 7 yr to recoup the difference. Because we cannot fully account for the maintenance costs (materials and personnel) for both systems, we assume they are equivalent, which likely underestimates the costs of the GELI given it is a technology of greater mechanical complexity. Though there is some uncertainty in the power costs of aeration (see discussion of errors below) our estimates delineate the major differences in the cost structure of these technologies to be in maintenance (aeration costs less) and power consumption (GELI costs less).

Our calculations of GELI efficiency and aeration airflows were based on our ability to accurately model the untreated thermal regime of Crystal Lake in the 2 treatment years. We have some confidence in our ability to model untreated water temperatures. First, the low RMSE between observed and modeled lake stratification indices in untreated years 2011 and 2014 (Table 2) indicate our parameterization of DYRESM for Crystal Lake is suitable insofar as 2011 and 2014 are generally representative of untreated 2012 and 2013 conditions. This assumption is particularly sensitive to K_d , the only empirically derived parameter we input to DYRESM, a parameter that is significant to the heat budget of a lake. Another confirmation in the accuracy of our modeling is that hypolimnetic warming rates of simulated

untreated 2012 (0.08 C/week) and 2013 (0.07 C/week) are similar to those observed during untreated years 2011 (0.09 C/week) and 2014 (0.11 C/week). Furthermore, bottom water temperatures of untreated 2012 were 1.0 C warmer in mid-September than at the same time in untreated 2013. We expect this because processes governing heat transfer to the hypolimnion of temperate lakes (i.e., diel heating and cooling prior to the onset of seasonal stratification; Wetzel 2001) were active approximately 1 mo longer in 2012 due to the early 2012 ice-off. Our ability to accurately model the untreated thermal regime of Crystal Lake allows us to isolate and remove the component of mechanical efficiency resulting from natural changes to potential energy. By removing the natural component our bias for higher mechanical efficiencies is reduced. However, our estimates of efficiency are simplifications and are not without error. Days of negative efficiency are days when changes in modeled PE decreased faster than observed. On these days we were unable to account for true reductions in PE resulting in negative efficiency estimates, thereby reducing overall average efficiency. Our ability to model the untreated thermal regime of Crystal Lake with DYRESM provides a basis for our application of the DYRESM aeration subroutine because these 2 models act in tandem to predict thermal response to aeration. The overall trends of temperature range created by the GELI were reproduced well by DYRESM aeration. Studies have demonstrated that DYRESM aeration simulations agree qualitatively with lake thermal responses to field applications of aeration (Patterson and Imberger 1989, Schladow 1993, Schladow and Fisher 1995). However, Moshfeghi et al. (2005) reported uncertainty in translation of airflows, particularly that the subroutine overestimates destratification per unit airflow. We therefore consider aeration airflow requirements resulting from our DYRESM simulations to be conservative approximations of what an aeration system would have required to match the destratification achieved by the GELI. This suggests our aeration power costs are likely underestimates and the true difference between the GELI and aeration is greater.

Recommendations for development

We have a few recommendations for improvement of the GELI that could increase mixing capacity and efficiency, decrease maintenance, and further improve

upon the current version of this technology. One improvement to mixing capacity and efficiency could be obtained by constraining the surface of the GELI to be parallel with the surface of the lake. This would ensure maximized drag-induced mixing as the GELI rises and falls through the water column. In our application at Crystal Lake, the GELI would ascend at a reasonably slow rate and maintain this optimal orientation with the lake surface but would fall through the water column at a sharp angle thereby losing mixing effectiveness. The optimal orientation could be obtained by fixing the GELI into a vertical track. By doing so the risk of sediment resuspension could be reduced by placing a stopping point above the sediment–water interface. Another area for improved performance is to reduce the size of the compressor or regulate compressor operation with a pressure-based switch. This could eliminate the pressure equilibration phase of the GELI cycle and reduce airflow requirements by approximately 25% and thus increase GELI efficiencies and reduce power costs. Finally, a significant number of personnel hours were spent observing and adjusting the GELI system. Incorporating sensors within the system would facilitate automated system control and a more consistent performance.

In conclusion, thermal stratification plays a vital role in regulating a broad range of biogeochemical and biological processes in lakes. Water quality problems arising from hypolimnetic anoxia can be managed with artificial mixing and destratification. In our study, we used the novel GELI lake mixing technology to gradually destratify Crystal Lake, Wisconsin, a lake that is 2 orders of magnitude larger than previously treated with the GELI. The slow mixing and destratification of the GELI was effective at reducing late-summer hypoxia and preventing fall anoxic conditions at the very bottom of the lake and was achieved at greater mechanical efficiencies than reported in field applications of bubble plume aeration. We estimate it would have taken aeration 1.4–1.8 times the airflow to achieve the same amount of destratification as the GELI during our 2-yr project, representing less of a contrast than reported in the original GELI case study. Though start-up and maintenance costs of the GELI are higher than aeration, and mixing capacity of the GELI needs to be increased, the potential for improvement is high and could be achieved in future versions leading to a new and practical lake mixing technology.

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References

- Antenucci J, Imerito A. 2003. The CWR Dynamic Reservoir Simulation Model DYRESM: User Manual. Crawley (WA): University of Western Australia Center for Water Research.
- Asaeda T, Imberger J. 1993. Structure of bubble plumes in linearly stratified environments. *J Fluid Mech.* 249:35–57.
- Birge EA. 1916. The work of the wind in warming a lake. *T Wisc Acad Sci.* 18(2):341–391.
- Bernhardt H. 1967. Aeration of Wahnbach Reservoir without changing the temperature profile. *J Am Water Works Assoc.* 59:943–964.
- Britton CM, Dodd JD. 1976. Relationships of photosynthetically active radiation and shortwave irradiance. *Agr Meteorol.* 17(1):1–7.
- Christodoulou GC. 1986. Interfacial mixing in stratified flows. *J Hydraul Res.* 24(2):77–92.
- Cooke GD, Carlson RE. 1989. Reservoir management for water quality and THM precursor control. Denver (CO): AWWA Research Foundation.
- Crawford TM, Duchon CE. 1999. An improved parameterization for estimating effective atmospheric emissivity for use in calculating daytime downwelling longwave radiation. *J Appl Meteorol.* 38:474–480.
- Fast AW. 1968. Artificial destratification of El Capitan Reservoir by aeration: effects on chemical and physical parameters. Sacramento (CA): Department of Fish and Game.
- Fast AW, Hulquist RG. 1982. Supersaturation of nitrogen gas caused by artificial aeration in reservoirs. US Army Engineer Waterways Experiment Station Final Report E-82-9.
- Ferraris C, Wilhm J. 1977. Distribution of benthic macroinvertebrates in an artificially destratified reservoir. *Hydrobiologia.* 54(2):169–176.
- Fischer HB, List EG, Koh RCY, Imberger J, Brooks NH. 1979. Mixing in inland and coastal waters. New York (NY): Academic Press.
- Gaeta JW, Read JS, Kitchell JF, Carpenter SR. 2012. Eradication via destratification: whole-lake mixing to selectively remove rainbow smelt, a cold-water invasive species. *Ecol Appl.* 22:817–827.
- Halsey TG. 1968. Autumnal and over-winter limnology of three small eutrophic lakes with particular reference to experimental circulation and trout mortality. *J Fish Res Board Can.* 25(1):81–99.
- Helfer F, Zang H, Lemckert C. 2011. Modelling of lake mixing induced by air-bubble plumes and the effects on evaporation. *J Hydrol.* 406(3–4):182–198.
- Ibelings BW, Backer LC, Kardinaal WEA, Chorus I. 2014. Current approaches to cyanotoxin risk assessment and risk management around the globe. *Harmful Algae.* 40:63–74.
- Imberger J, Patterson JC. 1981. A dynamic reservoir simulation model: DYRESM 5. In: Fischer HB (ed.). Transport models for inland and coastal waters. New York (NY): Academic Press. p. 310–361.
- Kenoyer GJ, Anderson MP. 1989. Groundwater's dynamic role in regulating acidity and chemistry in a precipitation-dominated lake. *J Hydrol.* 109:287–306.
- Kirke B, Gezawy A. 1997. Design and model tests for an efficient mechanical circulator/aerator for lakes and reservoirs. *Water Res.* 31:1283–1290.
- Klapper H. 2003. Technologies for lake restoration. *J Limnol.* 62:73–90.
- Lawson ZJ, Vander Zanden MJ, Smith CA, Heald E, Hrabik TR, Carpenter SR. 2015. Experimental mixing of a north-temperate lake: testing the thermal limits of a cold-water invasive fish. *Can J Fish Aquat Sci.* 72:926–937.
- Lydersen E, Aanes KJ, Andersen S, Andersen T, Brettum P, Baekken T, Lien L, Lindstrom EA, Lovik JE, Mjelde M, et al. 2008. Ecosystem effects of thermal manipulation of a whole lake, Lake Breisjoen, southern Norway (THERMOS project). *Hydrol Earth Syst Sci.* 12:509–522.
- Magnuson JJ, Kratz TK, Benson BJ. 2006. Long-term dynamics of lakes in the landscape: long-term ecological research on north-temperate lakes. Oxford (UK): Oxford University Press on Demand.
- Miles NG, West RJ. 2011. The use of an aeration system to prevent thermal stratification of a freshwater impoundment and its effect on downstream fish assemblages. *J Fish Biol.* 78:945–952.
- Moshfeghi H, Shahidi AE, Imberger J. 2005. Modeling of bubble plume destratification using DYRESM. *J Water Supply Res T.* 54(1):37–46.
- Pastorok RA, Lorenzen MW, Ginn TC. 1982. Environmental aspects of artificial aeration and oxygenation of

- reservoirs: a review of theory, techniques, and experiences. US Army Corps of Engineers Technical Report E-82-3.
- Patten BC, Egloff DA, Richardson TH. 1975. Total ecosystem model for a cove in Lake Texoma. In: Patten BC (ed.). System analysis and simulation in ecology. New York (NY): Academic Press. p. 206–423.
- Patterson JC, Imberger J. 1989. Simulation of bubble plume destratification systems in reservoirs. *Aquat Sci.* 51(1): 3–18.
- Perron T, Chetelat J, Gunn J, Beisner BE, Amyot M. 2014. Effects of experimental thermocline deepening on methylmercury bioaccumulation in a Canadian Shield Lake. *Environ Sci Technol.* 48:2626–2634.
- Pieters R, Coedy W, Ashley KI, Lawrence GA. 2015. Artificial circulation of a mine pit lake. *Can J Civil Eng.* 42: 33–43.
- Postel SL, Carpenter SR. 1997. Freshwater ecosystem services. In: Daily G (ed.). *Nature's services*. Washington (DC): Island Press. p. 195–214.
- Read JS, Hamilton DP, Jones ID, Muraoka K, Winslow LA, Kroiss R, Wu CH. 2011a. Derivation of lake mixing and stratification indices from high-resolution lake buoy data. *Environ Modell Softw.* 26(11):1325–1336.
- Read JS, Shade A, Wu CH, Gorzalski A, McMahon KD. 2011b. Gradual entrainment lake inverter (GELI): a novel device for experimental lake mixing. *Limnol Oceanogr-Meth.* 9:14–28.
- Sahoo GB, Luketina D. 2006. Response of a tropical reservoir to bubbler destratification. *J Environ Eng-ASCE.* 132: 736–746.
- Sastri AR, Gauthier J, Juneau P, Beisner BE. 2014. Biomass and productivity responses of zooplankton communities to experimental thermocline deepening. *Limnol Oceanogr.* 59:1–16.
- Schladow SG. 1993. Lake destratification by bubble-plume systems: design methodology. *J Hydraul Eng-ASCE.* 119:350–368.
- Schladow SG, Fisher IH. 1995. The physical response of temperate lakes to artificial destratification. *Limnol Oceanogr.* 40:359–373.
- Shade A, Read JS, Younblut ND, Fierer N, Knight R, Kratz TK, Lottig NR, Roden EE, Stanley EH, Stombaugh J, et al. 2012. Lake microbial communities are resilient after a whole-ecosystem disturbance. *ISME J.* 6: 2153–2167.
- Spigel RH, Imberger J, Rayner KN. 1986. Modeling the diurnal mixed layer. *Limnol Oceanogr.* 31:533–556.
- Stephens R, Imberger J. 1993. Reservoir destratification via mechanical mixers. *J Hydraul Eng-ASCE.* 119: 438–457.
- Strohmeier T, Strand O, Alunno-Bruscia M, Duinker A, Rosland R, Aure J, Erga SR, Naustvoll LJ, Jansen HM, Cranford PJ. 2015. Response of *Mytilus edulis* to enhanced phytoplankton availability by controlled upwelling in an oligotrophic fjord. *Mar Ecol-Prog Ser.* 518: 139–152.
- Stull RB. 1988. *An introduction to boundary layer meteorology*. Norwell (MA): Kluwer Academic Publishers.
- Sverdrup HU. 1953. On conditions for the vernal blooming of phytoplankton. *ICES J Mar Sci.* 18(3):287–295.
- Symons JM, Irwin WH, Robinson EL, Robeck GG. 1967. Impoundment destratification for raw water quality control using either mechanical or diffused air pumping. *J Am Water Works Assoc.* 59(10):1268–1291.
- Westgard RL. 1964. Physical and biological aspects of gas-bubble disease in impounded adult chinook salmon at McNary spawning channel. *T Am Fish Soc.* 93(3):306–309.
- Wetzel RG. 2001. *Limnology: lake and river ecosystems*. 3rd ed. San Diego (CA): Academic Press.
- Wuest A, Brooks NH, Imboden DM. 1992. Bubble plume modeling for lake restoration. *Water Resour Res.* 28(12):3235–3250.
- Yeates PS, Imberger J. 2003. Pseudo two-dimensional simulations of internal and boundary fluxes in stratified lakes and reservoirs. *Int J River Basin Manage.* 1(4):297–319.