Technical Note

# Effect of Artificial Circulation on the Removal Kinetics of Cyanobacteria in a Hypereutrophic Shallow Lake

Carlos H. A. Pacheco[1] and Iran E. Lima Neto[2]

**Abstract:** This study consisted of two parts. First, pre-aeration tests were conducted to assess the space-time variability of water quality in a shallow lake. Chlorophyll-a concentration and cyanobacteria cell density varied from 40 to 80 $\mu$g $L^{-1}$ and 0.5–2.0 $\times 10^6$ cells/mL, respectively. In the second and major part of the study, aeration tests were carried out to investigate the influence of artificial circulation on the flow hydrodynamics and water quality. Comparison of the measurements taken inside and outside the bubble plumes showed that artificial circulation promotes a faster decay of chlorophyll-a concentration over time. First-order kinetics fitted well the time-variation of depth-averaged chlorophyll-a, cyanobacteria, and pheophytin-a. The net reduction rate of chlorophyll-a and cyanobacteria could be described as a function of a dimensionless parameter $\beta$ that controls bubble plume hydrodynamics or, alternatively, as a function of the rate of dissipation of turbulent kinetic energy $\varepsilon$. This net reduction rate of chlorophyll-a could also be linearly related to the net growth rate of pheophytin-a. This suggests that algal removal was caused mainly by cellular death. Finally, the relationships obtained in this study were used to predict the impact of artificial circulation on algal removal in water-supply reservoirs. **DOI: 10.1061/(ASCE)EE.1943-7870.0001289.** *© 2017 American Society of Civil Engineers.*

**Author keywords:** Aeration; Algae; Bubble plumes; Chlorophyll-a; Pheophytin-a; Turbulence.

## Introduction

Eutrophication of water bodies is a worldwide problem with many adverse effects related with toxic cyanobacteria blooms (Paerl and Otten 2013; Ibelings et al. 2016). This is a critical issue in the Brazilian Northeast, a highly populated semiarid region (~50 million inhabitants) with more than 200,000 water-supply reservoirs (capacities of $10^{-1}$ to $10^4$ $hm^3$), which has faced several human losses because of cyanotoxin poisoning (Bouvy et al. 2000). Currently, it is estimated that more than 80% of the previously mentioned reservoirs are eutrophic or hypereutrophic, and many of them are no longer suitable for water supply, unless non-conventional water treatment plants are used to remove the cyanobacteria and their associated toxins (Capelo-Neto and Buarque 2016).

Artificial aeration and mixing systems have long been used to alleviate eutrophication symptoms in lakes and reservoirs. These systems normally use arrays of bubble plumes to induce surrounding liquid entrainment and destratify the water column (Wüest et al. 1992; Asaeda and Imberger 1993; Lima Neto et al. 2016). Many studies reported that artificially mixing the water column could limit light and nutrient availability, in order to minimize the undesired cyanobacteria blooms, or at least change the composition from cyanobacterial dominance to green algae and diatoms (Reynolds et al. 1983; Visser et al. 1996, 2016; Imteaz and Asaeda 2000; Heo and Kim 2004; Antenucci et al. 2005; Becker et al. 2006). Alternatively, bubble plumes have been adopted to oxygenate the hypolimnion and reduce phosphorus release from the lake sediments, and then inhibit algal growth (Soltero et al. 1994; Bormans et al. 2016).

All the aforementioned studies on bubble plumes were carried out under stratified water conditions in relatively deep lakes and reservoirs. On the other hand, laboratory experiments using different mixing devices in unstratified tanks have suggested that small-scale turbulence can influence algal growth by affecting cellular activities, promoting cell disruption, and/or changing the settling velocity of the cells (Thomas and Gibson 1990; Hondzo and Lyn 1999; Ruiz et al. 2004; Warnaars and Hondzo 2006; Berdalet et al. 2007; Carvalho Neto et al. 2014; Fraisse et al. 2015). However, the effect of small-scale turbulence on algal dynamics and metabolic rates is still unclear, and the results obtained from different experimental studies may not be representative of natural environments, such as lakes and reservoirs.

The present study is the first attempt on investigating the effect of flow circulation and turbulence induced by point-source bubble plumes on the growth/loss rate of cyanobacteria in a shallow unstratified lake. The goals were to analyze the hydrodynamics and water quality behavior inside and outside the bubble plumes to quantify the removal kinetics of cyanobacteria and obtain a predictive model for management of algal blooms in eutrophic water bodies. This is particularly important in the high-density reservoir network of the Ceará State, Brazilian Northeast (Lima Neto et al. 2011), where the rational use of point-source bubble plumes in the vicinity of water-supply intakes has been proposed as a relatively simple measure to minimize the local impacts of eutrophication and reduce water treatment costs.

## Materials and Methods

### Study Area and Aeration System

The field surveys were carried out in the Santo Anastácio Lake, located in the city of Fortaleza, Ceará, Brazil (Fig. 1). This tropical

[1]Ph.D. Student, Dept. of Hydraulic and Environmental Engineering, Federal Univ. of Ceará, Campus do Pici, bl. 713, 60.451-970, Fortaleza, Brazil.

[2]Assistant Professor, Dept. of Hydraulic and Environmental Engineering, Federal Univ. of Ceará, Campus do Pici, bl. 713, 60.451-970, Fortaleza, Brazil (corresponding author). E-mail: iran@deha.ufc.br

Note. This manuscript was submitted on April 11, 2017; approved on June 15, 2017; published online on October 4, 2017. Discussion period open until March 4, 2018; separate discussions must be submitted for individual papers. This technical note is part of the ***Journal of Environmental Engineering***, © ASCE, ISSN 0733-9372.

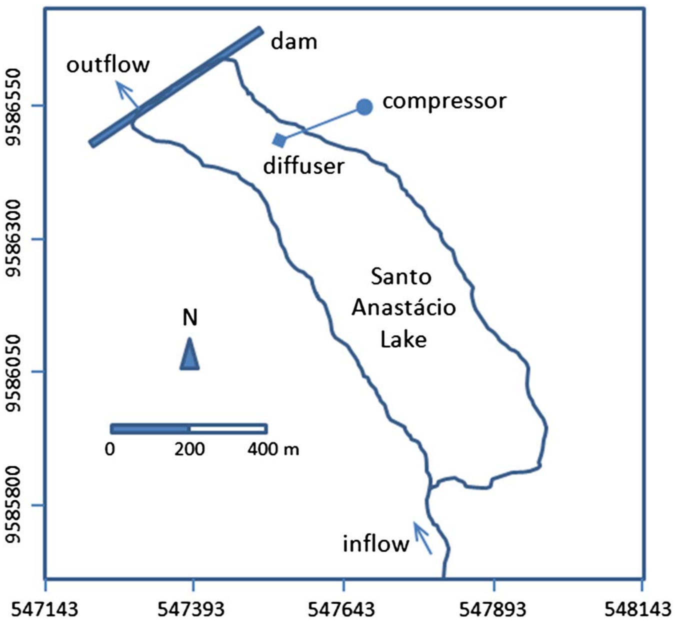


**Fig. 1.** Schematic of the Santo Anastácio Lake, in Fortaleza, Ceará, Brazil, showing the location of the air diffuser supplied by the compressor

lake has a volume of approximately 0.3 $hm^3$, maximum water depth of 3.8 m, and negligible thermal stratification, with a temperature difference between the lower and upper water layers of up to approximately 1°C. Despite its very short residence time of around a month, the reservoir is currently in a hypereutrophic state because of the high catchment nutrient loading (Antenucci et al. 2003). The air injection system consisted of a 7.5 kW compressor that provided atmospheric air flow rates $Q = 1$–$10$ $NLs^{-1}$ to a point-source diffuser placed at the bottom of the lake, approximately 30 m from the shore, where the water depth $z = 1.5$ m (Fig. 2). The diffuser consisted of an array of 1-in. PVC pipes with a total of 160 holes of 1 mm diameter, which was designed to promote high mixing efficiency and prevent clogging. The air flow rates per orifice were similar to those of Lima Neto et al. (2008), in which bubbles with diameters ranging from approximately 6–8 mm were formed. This agrees well with the values of 6.6–8.1 mm calculated from the correlation proposed by Lima Neto (2015).

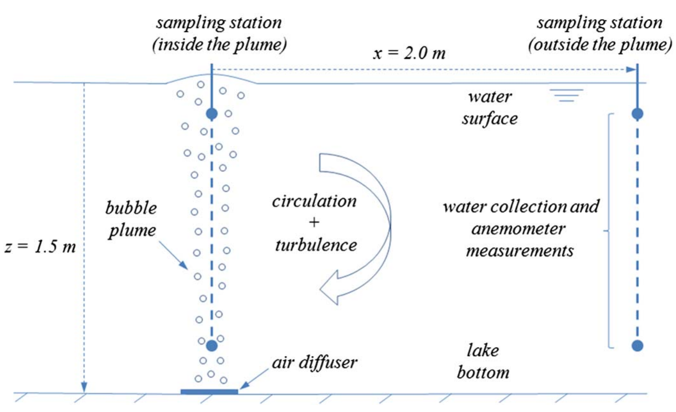


**Fig. 2.** Definition sketch of the bubble plume and sampling stations

### Hydrodynamic Measurements and Water Quality Sampling

The first part of the field studies was conducted during the dry season of November 2013 to assess the natural variability of water quality in the lake around the air diffuser site, but without aeration. The second part was conducted during the dry season of November 2014 to investigate the effect of artificial circulation on the flow hydrodynamics and water quality around the diffuser (Fig. 2). Hydrological parameters including solar exposure, air temperature, precipitation, and wind speed were measured in a meteorological station located at approximately 500 m from the Santo Anastácio Lake outlet. During the measurements, the water inflow was relatively low (~50 $Ls^{-1}$) so that natural mixing processes in the lake were driven mainly by wind shear (average speed of 3–5 m/s). Air and water temperatures varied between 25 and 30°C, and precipitation was nil. Water samples were collected around the diffuser area using Van Dorn bottles mounted on a stem connected to a thoroughly anchored boat.

The aeration tests were carried out with atmospheric air flow rates $Q$ of 1.9, 3.8, 5.7, and 7.6 $NLs^{-1}$, which were measured with a plastic tube rotameter. An electromagnetic propeller anemometer was used to measure the vertical water velocity inside the bubble plume and the horizontal water velocity outside the plume, following the circulation flow patterns described by Toné et al. (2017). The same propeller anemometer has been used by Lima Neto et al. (2008) to measure the water velocity in laboratory bubble plumes. Each aeration test had a duration of 120 min. The tests were performed at different times on a single day (November 29, 2014), with 120 min interval between tests: (1) from 6:00 to 8:00 (for $Q = 1.9$ $NLs^{-1}$); (2) from 10:00 to 12:00 (for $Q = 3.8$ $NLs^{-1}$); (3) from 14:00 to 16:00 (for $Q = 5.7$ $NLs^{-1}$); and (4) from 18:00 to 20:00 (for $Q = 7.6$ $NLs^{-1}$). In order to investigate the effect of artificial circulation on water quality for each aeration test, water samples using Van Dorn bottles were collected every 5–30 min at different depths $z$ and radial distances $x$ from the plume centerline (Fig. 2). For the qualitative analyses, samples of 500 mL were collected with plankton nets (20 $\mu$m mesh size) and placed in plastic bottles. Additional tests were conducted on November 11, 2014, for $Q = 3.8$ and 5.7 $NLs^{-1}$ to verify the repeatability of the results.

### Data Analysis

For the pre-aeration tests, the daily variations of hydrological and water quality parameters were analyzed in order to observe possible relationships with algal dynamics. Additionally, algal concentrations at different distances $x$ from the diffuser site were also compared to verify possible correlations. Laboratory analyses included: dissolved oxygen (modified Winkler method), nitrate nitrogen, nitrite nitrogen, ammonia-nitrogen, total phosphorus, orthophosphate, chlorophyll-a, and pheophytin-a (spectrophotometric method), as described by the APHA (2005). The identification and counting of algal cells were conducted by the light-field and inverted microscope methods, respectively. All the analyses were performed within a maximum of 12 hours after collection.

The same laboratory analyses and procedures described previously were also performed for each aeration test, so that the impact of artificial circulation on algal dynamics could be evaluated. The water velocities measured with the electromagnetic propeller anemometer were processed in *MATLAB* to generate circulation flow patterns induced by the bubble plumes. The idea was to identify the $x$ positions outside the plumes in which the water velocities become too small to be measured by anemometer so that the effect of flow circulation could be neglected. Hence, the authors assumed that water samples collected far enough from the plume could be used to represent the natural variation of algal concentration, whereas those inside the plume could be used to describe the combined effects of natural variation and artificial circulation. Thus, the growth/loss rates of depth-averaged chlorophyll-a, pheophytin-a, and cyanobacteria could be estimated by fitting kinetic models to the data obtained inside and outside the bubble plume. Then, the resulting impact of artificial circulation on algal dynamics could be evaluated by subtracting these two growth/loss rates. Finally, the authors performed curve fitting to obtain general models to describe the kinetics of cyanobacteria as a function of bubble plume hydrodynamics.

## Results and Discussion

### Analysis of Pre-Aeration Test Results

Fig. 3 shows typical daily variations of hydrological and water quality parameters obtained for Santo Anastácio Lake during the dry season of November 2013. Chlorophyll-a concentrations varied from approximately 40 to 80 $\mu$g $L^{-1}$, whereas cyanobacteria cell density varied from approximately 0.5 to $2.0 \times 10^6$ cells/mL, with the predominant species being the toxic *Aphanocapsa*. Consistently, Fig. 3 shows a similar trend for these two variables, with the peak occurring around 14:00 h, when the solar exposure and temperature also reached their maximum values. The increase in the oxygen level and the decrease in the nitrogen concentration up to this peak period may also be a consequence of photosynthesis and nutrient uptake, respectively. However, because the concentrations of total nitrogen and phosphorus were of the same order, both nutrients potentially play a relevant role in algal physiology. It is important to mention that the correlation coefficients between the chlorophyll-a concentrations at the diffuser site (at $x = 0$) and 2 m away were higher than 80%. This suggests that the distance of 2 m between sampling stations was small enough so that no significant differences in the natural behavior of algal dynamics was observed during the pre-aeration tests. Velocity data shown later in this section (Fig. 4) will also confirm this natural behavior 2 m away from the bubble plume. Therefore, the data obtained outside the diffuser site (at $x = 2$ m) will be considered here as a baseline.

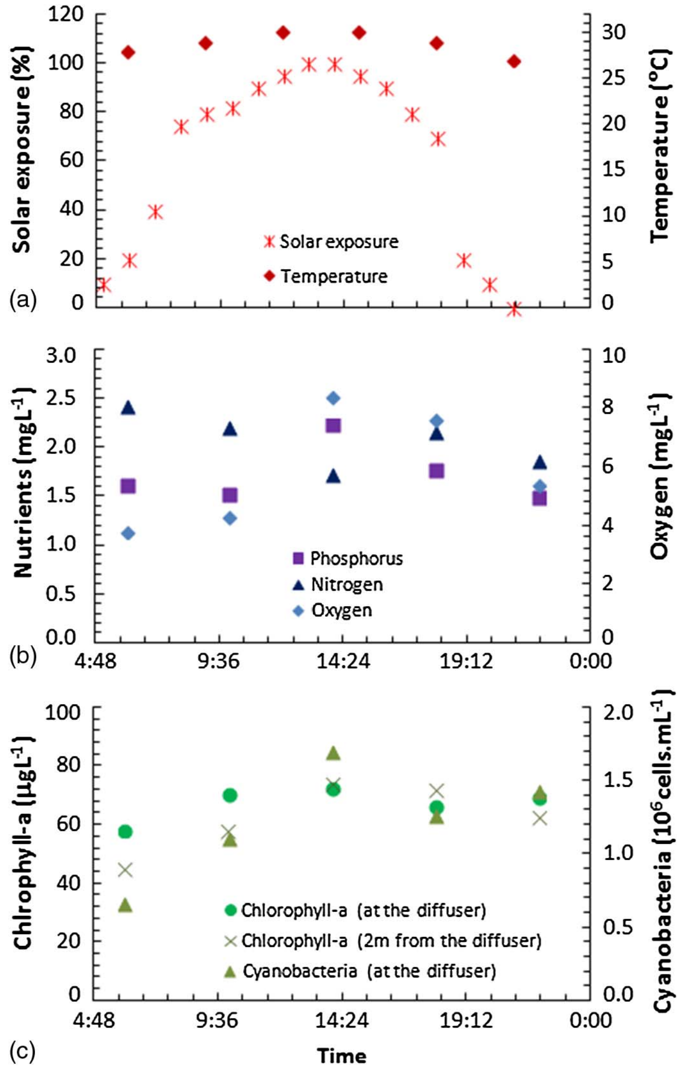


**Fig. 3.** Typical daily variations of hydrological and water quality parameters obtained for the Santo Anastácio Lake during the dry season of November 2013 (pre-aeration tests): (a) solar exposure and temperature; (b) nutrients and oxygen; (c) chlorophyll-a and cyanobacteria

### Analysis of Artificial Aeration Test Results

Fig. 4 shows a typical circulation flow pattern induced by the bubble plumes for an atmospheric air flow rate $Q = 7.6$ $NLs^{-1}$, which was generated in *MATLAB* from water velocity measurements taken during the aeration tests (November 2014). Maximum velocities of the order of 1.0 m/s occurred at the plume centerline (at $x = 0$), whereas minimum velocities of approximately 0.05 m/s occurred at $x = 1.5$ m. Similar flow patterns were obtained for the other air flow rates tested herein, but the velocities reduced as the air flow rates decreased. The velocities obtained in this study were very close to those simulated with the model of Lima Neto (2012), which estimated that up to approximately 40% of the total momentum flux induced by the bubble plumes was carried by turbulence. This information is important because turbulence can regulate algal dynamics by affecting sedimentation and nutrient acquisition (Fraisse et al. 2015). Note that water velocity data measured at $x = 2$ m were discarded because they approached the minimum value of 0.01 m/s that can be accurately measured by the anemometer. Observe that this velocity was of the same order of the shear velocity induced by the wind at the water surface (Fischer et al. 1979, p. 180). Therefore, the authors assumed that at $x = 2$ m

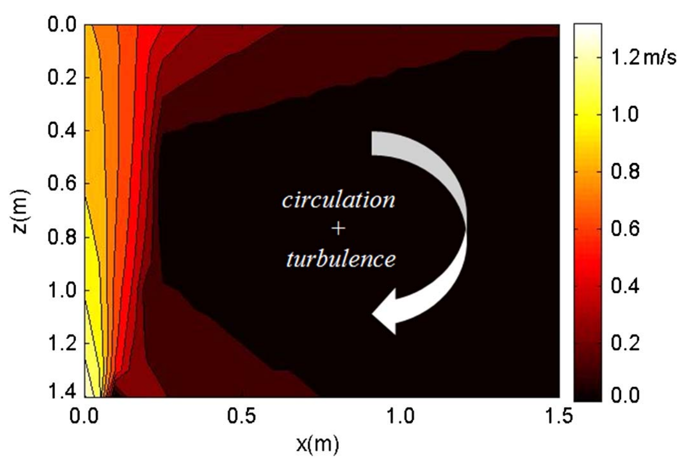


**Fig. 4.** Typical water circulation pattern induced by the bubble plumes for an atmospheric air flow rate $Q = 7.6$ $NLs^{-1}$ (November 2014); the air diffuser is located at $x = 0$ and $z = 1.4$ m

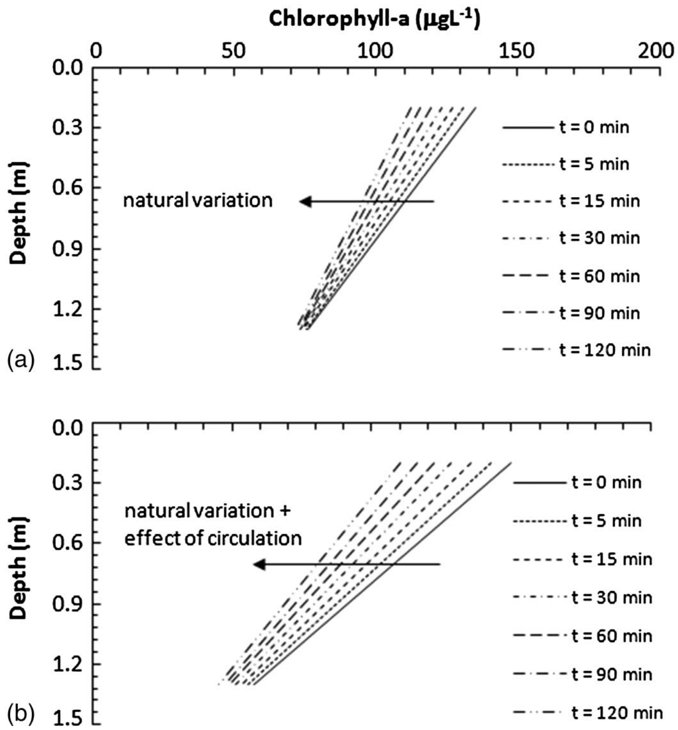


**Fig. 5.** Impact of artificial circulation ($Q = 3.8$ NLs$^{-1}$) on the decay of chlorophyll-a concentrations over time (November 2014): (a) outside the bubble plume (at $x = 2$ m); (b) inside the bubble plume (at $x = 0$); note that straight lines were fitted to the data obtained at two heights: 0.2 and 1.3 m

the impact of aeration-induced flow on algal dynamics was negligible as compared to that at the plume centerline (at $x = 0$).

At the end of each aeration test (duration of 120 min), the depth-averaged concentration of chlorophyll-a measured outside the bubble plume (at $x = 2$ m) was consistently higher (5–20%) than that obtained inside the plume (at $x = 0$), with the difference increasing with the atmospheric air flow rate $Q$. Fig. 5 shows an example of this positive impact of artificial circulation on algal dynamics for $Q = 3.8$ NLs$^{-1}$ (November 2014). It is clearly seen that circulation promotes a faster decay of chlorophyll-a concentrations over time inside the bubble plume than outside it. Similar trends were also observed for the cyanobacteria cell density data. On the other hand, the change in the other water quality parameters (temperature, nutrients, and dissolved oxygen) measured outside and inside the plume was within approximately $\pm 10\%$, with no clear trend with $Q$. This implies that artificial circulation causes decay in algal population, but does not affect significantly the other water quality parameters. Note that all the flow conditions studied here were turbulent and, according to previous investigations (Thomas and Gibson 1990; Hondzo and Lyn 1999; Ruiz et al. 2004; Warnaars and Hondzo 2006; Berdalet et al. 2007; Fraisse et al. 2015), flow turbulence affects algal physiology. Furthermore, artificial circulation may displace algae from the bubble plume surroundings, as pointed out by Toné et al. (2017). These two factors are potential causes of the more efficient removal of algae inside the bubble plume.

Fig. 6 shows the fitting of first-order kinetics to the variation of depth-averaged chlorophyll-a concentration over time inside (at $x = 0$) and outside (at $x = 2$ m) the bubble plumes, for the different air flow rates used in this study: (1) $Q = 1.9$ NLs$^{-1}$;

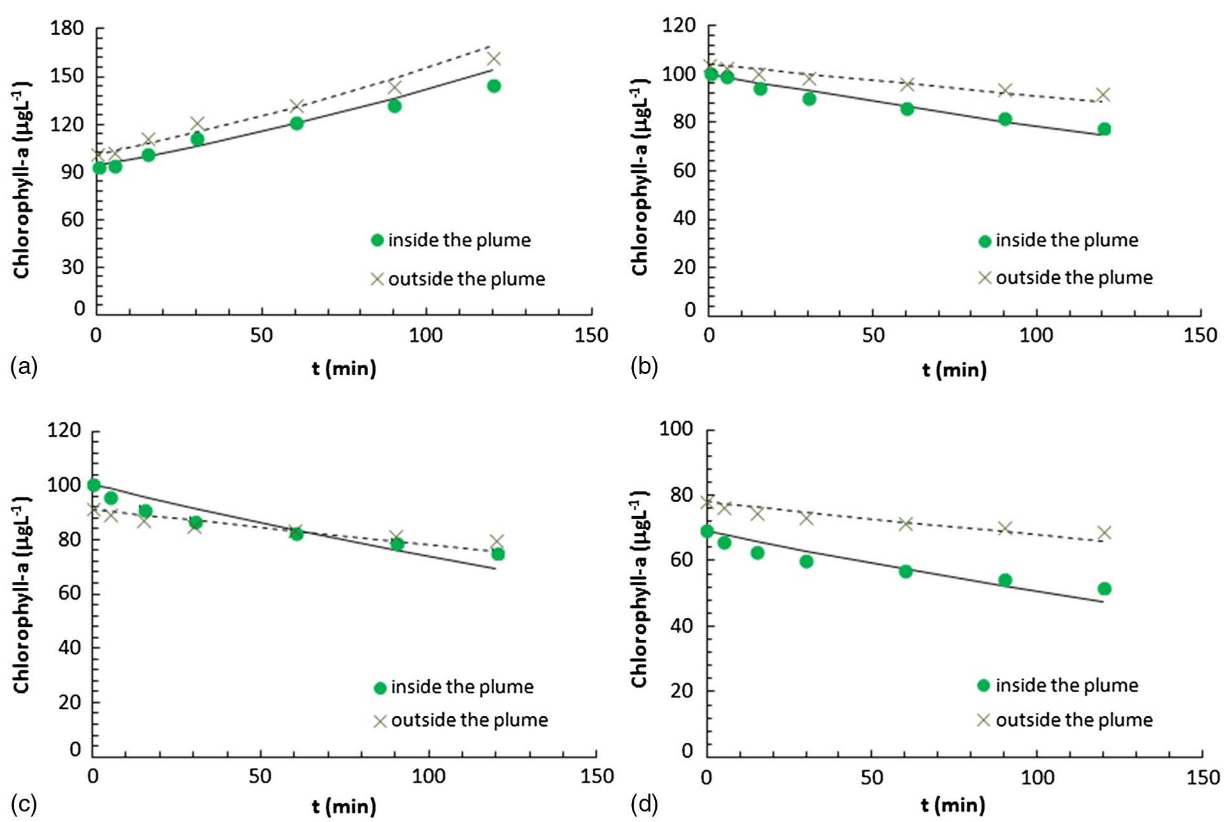


**Fig. 6.** Fitting of first-order kinetics to the variation of depth-averaged chlorophyll-a concentration over time inside (at $x = 0$) and outside (at $x = 2$ m) the bubble plumes: (a) $Q = 1.9$ NLs$^{-1}$; (b) $Q = 3.8$ NLs$^{-1}$; (c) $Q = 5.7$ NLs$^{-1}$; (d) $Q = 7.6$ NLs$^{-1}$

(2) $Q = 3.8$ NLs$^{-1}$; (3) $Q = 5.7$ NLs$^{-1}$; and (4) $Q = 7.6$ NLs$^{-1}$. A good fit was obtained for all the experimental conditions, with correlation coefficients higher than 0.97. Similar curves were also obtained for the data of cyanobacteria, with correlation coefficients also greater than 0.97. For the first test [Fig. 6(a)], the chlorophyll-a concentration increased over time both inside and outside the plume, but the growth rate inside the plume was slightly lower than that outside the plume. On the other hand, for the other three tests [Figs. 6(b–d)], the chlorophyll-a concentration decreased over time both inside and outside the plume, but the loss rate inside the plume was higher than that outside the plume. Observe that this difference increased with the air flow rate. These results confirm that artificial circulation acts as an algae removal factor for all the cases. Thus, the following exponential decay curve can be obtained to describe the kinetics of the reduction of depth-averaged chlorophyll-a concentrations over time due to artificial circulation:

$$[\text{Chl-a}] = [\text{Chl-a}]_o \exp(-kt) \tag{1}$$

where [Chl-a] = chlorophyll-a concentration at time $t$ ($\mu$g L$^{-1}$); $[\text{Chl-a}]_o$ = initial chlorophyll-a concentration ($\mu$g L$^{-1}$); and $k$ = net reduction rate of chlorophyll-a concentration (day$^{-1}$), which is given by $k = k_{\text{in}} - k_{\text{out}}$, where $k_{\text{in}}$ and $k_{\text{out}}$ are the growth/loss rates adjusted to the data obtained inside and outside the bubble plume, respectively (Fig. 6).

In order to obtain a general model to predict the removal kinetics of cyanobacteria in eutrophic lakes, the authors used the following dimensionless parameter defined by Lima Neto (2012) to describe the hydrodynamics of bubble plumes:

$$\beta = \frac{g'Q}{z_d u_s^3} \tag{2}$$

where $g'$ = reduced gravity (ms$^{-2}$), given by $g' = g(\rho_w - \rho_g)$, where $\rho_w$ and $\rho_g$ are the water and air densities (kg m$^{-3}$), respectively; $Q$ = atmospheric air flow rate (Nm$^3$ s$^{-1}$); $z_d$ = water head above the diffuser (m); and $u_s$ = bubble slip velocity (m/s). For the bubble diameters expected in this study (6–8 mm), the bubble slip velocity assumes a constant value of $u_s = 0.23$ m/s (Wüest et al. 1992). Fig. 7(a) shows that the net reduction rate of chlorophyll-a given by the first-order coefficient $k$ can be described as a function of $\beta$, with a correlation coefficient of 0.99. This results in the following relationship:

$$k = 1.61\ln(\beta) + 0.33 \tag{3}$$

The repeatability of the results was verified for $Q = 3.8$ and 5.7 NLs$^{-1}$, which resulted in deviations of the $k$-values shown in Fig. 7(a) of ±20%. Thus, error bars (±20%) were included in the figure, assuming the same deviations for the other flow conditions. The values of $k$ obtained from the data of cyanobacteria cell density (instead of chlorophyll-a concentration) were also plotted in Fig. 7(a) to confirm the effect of $\beta$ on the removal kinetics of cyanobacteria (correlation coefficient of 0.96).

The effect of turbulence on algal removal is evaluated in Fig. 7(b). The authors used the correlation proposed by García and García (2006) to obtain the rate of dissipation of turbulent kinetic energy $\varepsilon$ (cm$^2$ s$^{-3}$), which is given as a function of the air flow rate: $\varepsilon = 0.0116Q^{1.426}$. Fig. 7(b) shows that the removal coefficient $k$ can also be described by $\varepsilon$, with a correlation coefficient of 0.99. Eq. (4) represents this relationship:

$$k = 1.13\ln(\varepsilon) + 4.37 \tag{4}$$

The increase in the algal removal coefficient $k$ with the turbulent dissipation $\varepsilon$ is consistent with the studies reported by Thomas and Gibson (1990), Hondzo and Lyn (1999), and Berdalet et al. (2007), in which phytoplankton growth inhibition has been observed for similar ranges of $\varepsilon$ in the laboratory scale. Data of cyanobacteria is also plotted in Fig. 7(b) to reinforce the behaviors shown in Fig. 7(a) (correlation coefficient of 0.96).

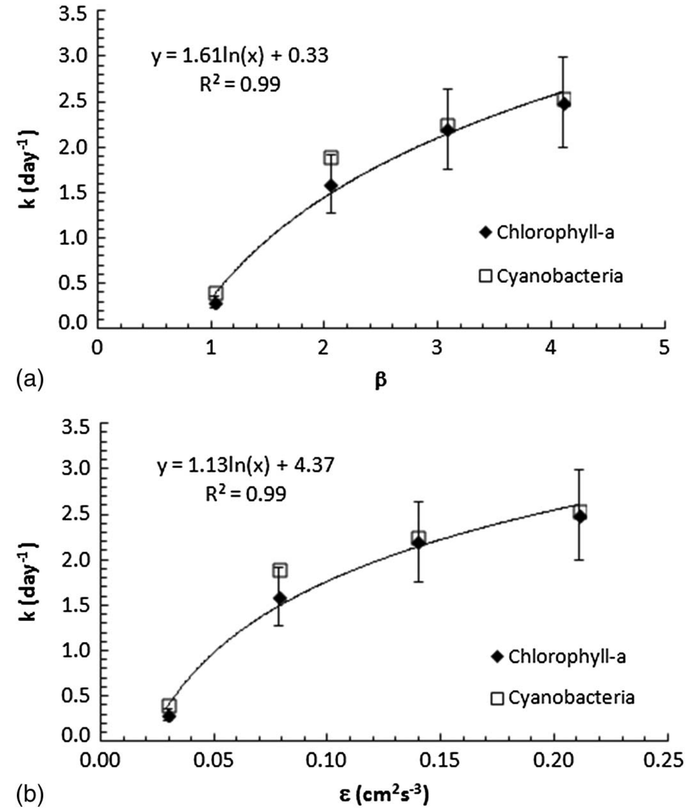


**Fig. 7.** Fitted relationships for the chlorophyll-a removal coefficient $k$ as a function of (a) the dimensionless parameter $\beta$ that describes bubble plume hydrodynamics; (b) the rate of dissipation of turbulent kinetic energy $\varepsilon$ (estimated from García and García 2006); data of cyanobacteria is also shown as a reference

Similar to Fig. 6, which was obtained from chlorophyll-a concentrations, Fig. 8 shows the fitting of first-order kinetics to the variation of depth-averaged pheophytin-a concentration over time inside (at $x = 0$) and outside (at $x = 2$ m) the bubble plumes, for the four air flow rates tested here: (1) $Q = 1.9$ NLs$^{-1}$; (2) $Q = 3.8$ NLs$^{-1}$; (3) $Q = 5.7$ NLs$^{-1}$; and (4) $Q = 7.6$ NLs$^{-1}$. Again, a good fit was obtained for all the experimental conditions, with correlation coefficients higher than 0.96. For the first case [Fig. 8(a)], the pheophytin-a concentration increased over time both inside and outside the plume, with approximately the same growth rate. On the other hand, for the other three cases [Figs. 8(b–d)], the pheophytin-a concentration decreased over time both inside and outside the plume, but the loss rate inside the plume was lower than that outside it. It is important to stress that this result is the opposite observed for the chlorophyll-a curves (Fig. 6) because pheophytin-a is a degradation product of chlorophyll-a. This suggests that artificial circulation promotes an increase in the pheophytin-a concentration, which is attributed to algal death. Therefore, the following curve can be used to describe the kinetics of the growth of depth-averaged pheophytin-a concentrations over time due to artificial circulation:

$$[\text{Pheo-a}] = [\text{Pheo-a}]_o \exp(k_{\text{pheo}} t) \tag{5}$$

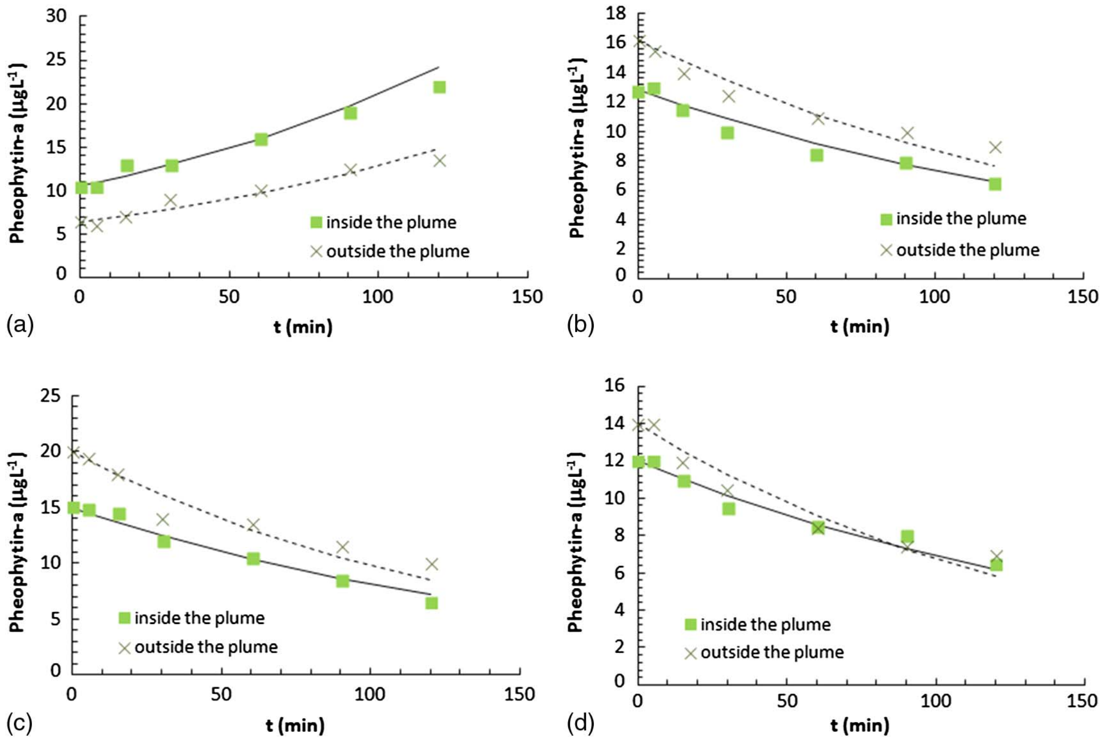


**Fig. 8.** Fitting of first-order kinetics to the variation of depth-averaged pheophytin-a concentration over time inside (at $x = 0$) and outside (at $x = 2$ m) the bubble plumes: (a) $Q = 1.9$ NLs$^{-1}$; (b) $Q = 3.8$ NLs$^{-1}$; (c) $Q = 5.7$ NLs$^{-1}$; (d) $Q = 7.6$ NLs$^{-1}$

where [Pheo-a] = pheophytin-a concentration at time $t$ ($\mu$g L$^{-1}$); $[\text{Pheo-a}]_o$ = initial pheophytin-a concentration ($\mu$g L$^{-1}$); and $k_{\text{pheo}}$ = net growth rate of pheophytin-a concentration (day$^{-1}$), which is given by $k_{\text{pheo}} = k_{\text{pheo,in}} - k_{\text{pheo,out}}$, where $k_{\text{pheo,in}}$ and $k_{\text{pheo,out}}$ are the growth/loss rates adjusted to the data obtained inside and outside the bubble plume, respectively (Fig. 8).

Fig. 9 shows the chlorophyll-a removal coefficient $k$ plotted as a function of the pheophytin-a growth coefficient $k_{\text{pheo}}$. Curve fitting yielded the linear relationship given by Eq. (6), with a correlation coefficient of 0.95. This confirms that algal removal was caused mainly by cellular death, which is explained by the chlorophyll-a degradation into pheophytin-a, as reported by Louda et al. (1998). Nevertheless, a small portion of the algal cells potentially escaped from the aeration site, as suggested by Toné et al. (2017)

$$k = 0.89k_{\text{pheo}} + 0.53 \tag{6}$$

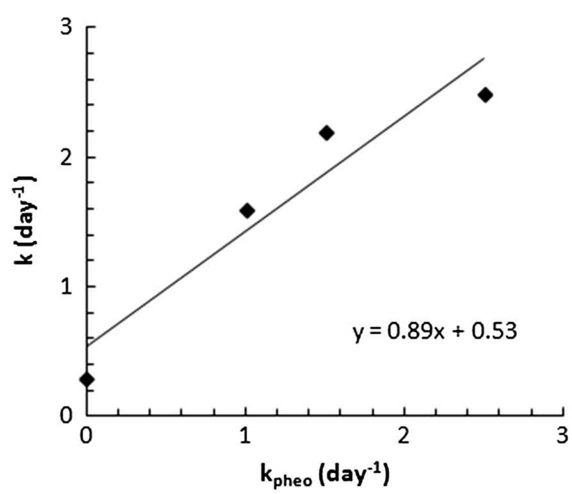


**Fig. 9.** Relationship between the chlorophyll-a removal coefficient $k$ and the pheophytin-a growth coefficient $k_{\text{pheo}}$

### Applications

As an application of the results, the relationships obtained in this study can be used to predict the impact of artificial circulation on algal removal in lakes and reservoirs. For example, most of the thousands of water-supply reservoirs in the State of Ceará, Brazil, are currently in a hypereutrophic state, with chlorophyll-a concentration frequently reaching the value of 60 $\mu$g L$^{-1}$, which is the

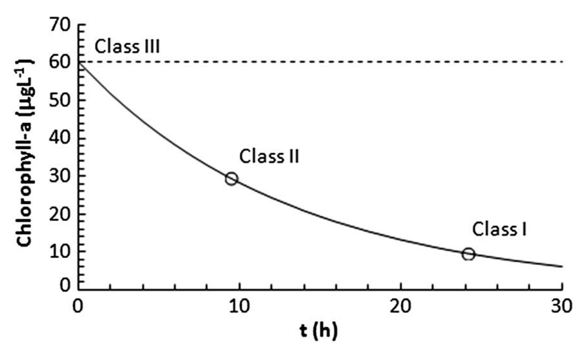


**Fig. 10.** Prediction of the impact of artificial circulation on chlorophyll-a concentration over time in a hypereutrophic reservoir; Classes I, II, and III refer to the Brazilian Surface Water Quality Standards

limit for Class III reservoirs, according to the National Surface Water Quality Standards (Ministério do Meio Ambiente and CONAMA 2005). Hence, if one considers a point-source bubble plume with an air flow rate of $Q = 10$ $NLs^{-1}$ being released at a water depth of 3.4 m, Eqs. (2) and (3) yield $\beta = 2.37$ and $k = 1.72$ $day^{-1}$, respectively. Thus, using Eq. (1), one would expect that within time frames of approximately 10 and 24 h the water quality at the air diffuser site would improve to Class II reservoirs (chlorophyll-a limit of 30 $\mu g\ L^{-1}$) and Class I reservoirs (chlorophyll-a limit of 10 $\mu g\ L^{-1}$), respectively, as depicted in Fig. 10. Note that in the present application the authors assumed a constant chlorophyll-a concentration (60 $\mu g\ L^{-1}$) in the reservoir. But in real reservoirs, where this concentration normally varies with time (Fig. 3), the algal decay model proposed here can be coupled with lake water quality models such as those of Gulliver and Stefan (1982) and Imteaz et al. (2003, 2009) to evaluate the impact of artificial aeration on lake water quality.

## Conclusions

Results from field surveys conducted in a hypereutrophic shallow lake in Brazil showed that artificial circulation induced by diffused aeration promotes a faster decay of algae over time, as compared to baseline data obtained outside the bubble plumes. The time variation of depth-averaged chlorophyll-a, pheophytin-a, and cyanobacteria were adjusted to first-order kinetic models, both inside and outside the bubble plumes. The net reduction rates of chlorophyll-a and cyanobacteria due to artificial circulation were well described by log-curves as a function of bubble plume hydrodynamics and flow turbulence. These algal reduction rates were also linearly related to the net growth rate of pheophytin-a, which suggests that algal removal was caused mainly by cellular death, which is accompanied by chlorophyll-a conversion into pheophytin-a. Additionally, the relationships proposed here were used to study the effect of artificial circulation on algal removal in eutrophic reservoirs. The simulations indicate that the use of point-source bubble plumes around water-supply intakes can be an effective measure to minimize the local impacts of eutrophication and potentially reduce the water treatment costs.

## Acknowledgments

The authors greatly appreciate the financial support provided by the Brazilian National Council for Scientific and Technological Development—CNPq (Project 476430/2011-9).

## References


Antenucci, J. P., Alexander, R., Romero, J. R., and Imberger, J. (2003). "Management strategies for a eutrophic water supply reservoir–San Roque, Argentina." *Water Sci. Technol.*, 47(7), 149–155.

Antenucci, J. P., Ghadouani, A., Burford, M. A., and Romero, J. R. (2005). "The long-term effect of artificial destratification on phytoplankton species composition in a subtropical reservoir." *Freshwater Biol.*, 50(6), 1081–1093.

APHA (American Public Health Association). (2005). *Standard methods for the examination of water and wastewater*, 21st Ed., Washington, DC.

Asaeda, T., and Imberger, J. (1993). "Structure of bubble plumes in linearly stratified environments." *J. Fluid Mech. Res.*, 249(Apr), 35–57.

Becker, A., Herschel, A., and Wilhelm, C. (2006). "Biological effects of incomplete destratification of hypertrophic freshwater reservoir." *Hydrobiologia*, 559(1), 85–100.

Berdalet, E., Peters, F., Koumandou, V. L., Roldán, C., Guadayol, Ò., and Estrada, M. (2007). "Species-specific physiological response of dinoflagellates to quantified small-scale turbulence." *J. Phycol.*, 43(5), 965–977.

Bormans, M., Maršálek, B., and Jančula, D. (2016). "Controlling internal phosphorus loading in lakes by physical methods to reduce cyanobacterial blooms: A review." *Aquat. Ecol.*, 50(3), 407–422.

Bouvy, M., Falcão, D., Marinho, M., Pagano, M., and Moura, A. (2000). "Occurrence of cylindrospermopsis cyanobacteria in 39 Brazilian tropical reservoirs during the 1998 drought." *Aquat. Microb. Ecol.*, 23(Dec), 13–27.

Capelo-Neto, J., and Buarque, N. M. S. (2016). "Simulation of saxitoxins adsorption in full-scale GAC filter using HSDM." *Water Res.*, 88(Jan), 558–565.

Carvalho Neto, R. G., et al. (2014). "Microalgae harvesting and cell disruption: A preliminary evaluation of the technology electroflotation by alternating current." *Water Sci. Technol.*, 70(2), 315–320.

Fischer, H. B., List, E. J., Koh, R. C. Y., Imberger, J., and Brooks, N. H. (1979). *Mixing in inland and coastal waters*, Academic Press, Cambridge, MA.

Fraisse, S., Bormans, M., and Lagadeuc, Y. (2015). "Turbulence effects on phytoplankton morphofunctional traits selection." *Limnol. Oceanogr.*, 60(3), 872–884.

García, C. M., and García, M. H. (2006). "Characterization of flow turbulence in large-scale bubble-plume experiments." *Exp. Fluids*, 41(1), 91–101.

Gulliver, J. S., and Stefan, S. (1982). "Lake phytoplankton model with destratification." *J. Environ. Eng. Div.*, 108(5), 864–882.

Heo, W. M., and Kim, B. (2004). "The effect of artificial destratification on phytoplankton in a reservoir." *Hydrobiologia*, 524(1), 229–239.

Hondzo, M., and Lyn, D. (1999). "Quantified small-scale turbulence inhibits the growth of a green alga." *Freshwater Biol.*, 41(1), 51–61.

Ibelings, B. W., Bormans, M., Fastner, J., and Visser, P. M. (2016). "CYANOCOST special issue on cyanobacterial blooms: Synopsis—A critical review of the management options for their prevention, control and mitigation." *Aquatic Ecol.*, 50(3), 595–605.

Imteaz, M. A., and Asaeda, T. (2000). "Artificial mixing of lake water by bubble plume and effects of bubbling operations on algal bloom." *Water Res.*, 34(6), 1919–1929.

Imteaz, M. A., Asaeda, T., and Lockington, D. (2003). "Modelling the effects of inflow parameters on lake water quality." *Environ. Model. Assess.*, 8(2), 63–70.

Imteaz, M. A., Shanableh, A., and Asaeda, T. (2009). "Modelling multi-species algal bloom in a lake and inter-algal competitions." *Water Sci. Technol.*, 60(10), 2599–2611.

Lima Neto, I. E. (2012). "Bubble plume modelling with new functional relationships." *J. Hydraul. Res.*, 50(1), 134–137.

Lima Neto, I. E. (2015). "Size of air bubbles formed from non-porous diffusers in water." *Engenharia Sanitária e Ambiental*, 20(2), 175–180 (in Portuguese).

Lima Neto, I. E., Cardoso, S. S. S., and Woods, A. W. (2016). "On mixing a density interface by a bubble plume." *Int. J. Fluid Mech. Res.*, 802(Sep), R3.

Lima Neto, I. E., Wiegand, M. C., and Araújo, J. C. (2011). "Sediment redistribution due to a dense reservoir network in a large semiarid Brazilian basin." *Hydrol. Sci. J.*, 56(2), 319–333.

Lima Neto, I. E., Zhu, D. Z., and Rajaratnam, N. (2008). "Air injection in water with different nozzles." *J. Environ. Eng.*, 10.1061/(ASCE)0733-9372(2008)134:4(283), 283–294.

Louda, J. W., Li, J., Liu, L., Winfree, M. N., and Baker, E. W. (1998). "Chlorophyll-a degradation during cellular senescence and death." *Org. Geochem.*, 29(5–7), 1233–1251.

*MATLAB* [Computer software]. MathWorks, Natick, MA.

Ministério do Meio Ambiente and CONAMA (Conselho Nacional do Meio Ambiente). (2005). "Dispõe sobre a classificação dos corpos de água e diretrizes ambientais para o seu enquadramento, bem como estabelece as condições e padrões de lançamento de efluentes, e dá outras providências." Diário Oficial da República Federativa do Brasil, Brasília, Brazil (in Portuguese).

Paerl, H. W., and Otten, T. G. (2013). "Harmful cyanobacterial blooms: Causes, consequences, and controls." *Microb. Ecol.*, 65(4), 995–1010.

Reynolds, C. S., Wiseman, S. W., Godfrey, B. M., and Butterwick, C. (1983). "Some effects of artificial mixing on the dynamics of phytoplankton populations in large limnetic enclosures." *J. Plankton Res.*, 5(2), 203–234.

Ruiz, J., Macías, D., and Peters, F. (2004). "Turbulence increases the average settling velocity of phytoplankton cells." *PNAS*, 101(51), 17720–17724.

Soltero, R. A., Sexton, L. M., Ashley, K. I., and McKee, K. O. (1994). "Partial and full lift hypolimnetic aeration of Medical Lake, WA to improve water quality." *Water Res.*, 28(11), 2297–2308.

Thomas, W. H., and Gibson, C. H. (1990). "Effects of small-scale turbulence on microalgae." *J. Appl. Phycol.*, 2(1), 71–77.

Toné, A. J., Pacheco, C. H., and Lima Neto, I. E. (2017). "Circulation induced by diffused aeration in a shallow lake." *Water SA*, 43(1), 36–41.

Visser, P. M., Bas, W., Ibelings, B. W., Veer, B. V. D., Koedood, J., and Mur, L. R. (1996). "Artificial mixing prevents nuisance blooms of the cyanobacterium Microcystis in Lake Nieuwe Meer, the Netherlands." *Freshwater Biol.*, 36(2), 435–450.

Visser, P. M., Ibelings, B. W., Bormans, M., and Huisman, J. (2016). "Artificial mixing to control cyanobacterial blooms: A review." *Aquat. Ecol.*, 50(3), 423–441.

Warnaars, T. A., and Hondzo, M. (2006). "Small-scale fluid motion mediates growth and nutrient uptake of Selenastrum capricornutum." *Freshwater Biol.*, 51(6), 999–1015.

Wüest, A., Brooks, N. H., and Imboden, D. M. (1992). "Bubble plume modeling for lake restoration." *Water Resour. Res.*, 28(12), 3235–3250.