The Interaction Between a Bubble Plume and the Near-field in a stratified medium: Implications for Water Quality Amelioration

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Abstract
Artificial destratification of the water column is a common means of addressing water quality problems with the most popular method of destratification being the bubble-plume diffuser. The air or oxygen distribution along submerged multiport diffusers is based on similar basic principles as those of outfall disposal systems. Moreover, the disposal of sequestered greenhouse gases into the ocean, as recently proposed by several researchers to mitigate the global warming problem, it requires an analogous design criteria. In this paper, the influence of a bubble-plume is evaluated using full-scale temperature and water quality data collected in the San Roque Reservoir, Argentina. A composite system consisting of seven separated diffusers connected to four 500 kPa compressors was installed at this reservoir at the end of 2008. The original purpose of the air bubble system was to reduce the stratification so that the water body may completely mix under natural phenomena and remain well oxygenated throughout the year. By using a combination of the field measurements and modeling, this work demonstrates that artificial mixing may improve water quality; if improperly sized or operated, however, such mixing can also cause deterioration. Any disruption in aeration during the destratification process, for example, may result in an accelerate decrease of oxygen levels due to the higher hypolimnetic temperatures.

Keywords
Bubble-plume; reservoir; near-field; stratification; water quality; eutrophication

INTRODUCTION

Eutrophication of reservoirs as a result of increasing settlement within the Central region of Argentina it has contributed to a number of water quality problems in waterbodies such as algal and cyanobacterial blooms, reduced recreational aesthetics, hypolimnetic oxygen depletion, reduced transparency and fish kills.

Artificial destratification of the water column is a common means of addressing the above water quality problems with the most popular method of destratification being the air bubble diffuser (Asaeda and Imberger 1993, McGinnis and Little 1998, Johnson *et al*. 2000, and others). This method uses pipes with holes, porous hoses, or porous diffusers to produce bubble columns, creating a gas-water mixture that is less dense than the surrounding water, and imparting momentum due to a positive buoyancy flux. The positively buoyant mixture rises and entrains water at the boundaries, which increases the water flow rate and cross-sectional area while decreasing the momentum. The plume overcomes the vertical density gradient until the depth of maximum plume rise is reached. At this stage, the plume water is negatively buoyant and falls back to the equilibrium depth, where the plume density matches the ambient density. Upon reaching the equilibrium depth, the plume spreads horizontally into the far-field.

The overall goal of this air bubble plume is to sufficiently reduce the stratification so that the water body may completely mix under natural phenomena and remain well oxygenated throughout. The energy required for complete mixing is dependent on the specific physico-chemical and hydromorphological characteristics of the waterbody, history of nutrient enrichment and local weather conditions. So, although the design of artificial destratification systems is based on theoretical hydrodynamic principles, the reservoir modelling tools used often do not consider the full range of environmental variability. This can lead to inadequate energy production for complete mixing when applied in practice. Other factors, such as lake depth, may also limit the success of artificial destratification systems, as was found in Chaffey Dam (Sherman *et al*. 2000). In this case, the average depth was too shallow to keep cyanobacteria out of eutrophic zone for periods long enough to reduce production through light limitation.

Mixing of thermally stratified water helps to homogenize dissolved oxygen (DO) conditions throughout the water by mixing higher constituent concentration surface water with lower DO concentration bottom water. Destratification in some situations can have then adverse impacts through eliminating coldwater habitat for fish and zooplankton, or distributing contaminants or nutrients from bottom areas with high concentration into the entire water column.

Artificial aeration of a reservoir is being first attempted in Argentina since October of 2008 in San Roque reservoir, Cordoba. Based on full-scale temperature data, this paper seeks to contribute to the understanding of the effects of the bubble plume destratification system on the physical mixing of San Roque Reservoir.

METHODOLGY

Study site

San Roque Reservoir was constructed by damming the river Suquia in 1891. It is a reservoir with a medium depth of 18 m, length of 10 km, and a maximum width of 3 km (Figure 1*a*). Its maximum volume is 200 million m^3 water and it covers an area of 16 km^2. The theorethical average retention time is 7 months. San Roque is a warm monomictic reservoir, experiencing thermal stratification between the months of November-March. During the stratification period, hypolimnetic oxygen depletion is severe. Prior to installation of destratification system, up to 40% of the lake volume experienced anoxia during summer months (Helmbrecht 2002). The light is highly attenuated with depth, being the maximum euphotic depth restricted to the first 2-3 m.

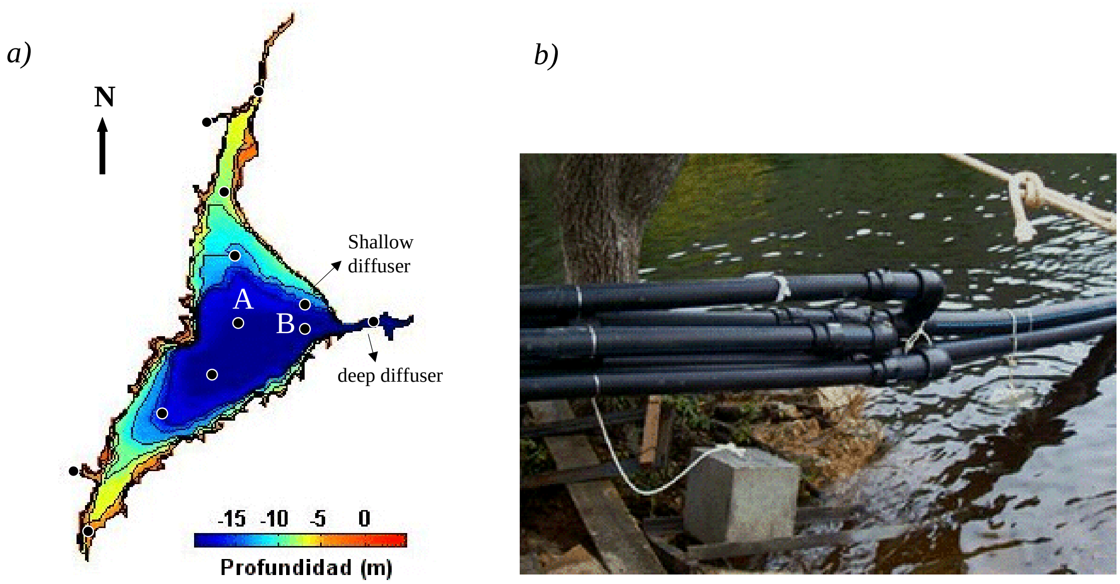

Figure 1. *a)* San Roque Reservoir bathymetry showing sampling stations (dots) and diffuser lines. *b)* Air supply pipes and anchor before being submerged into the reservoir water. The cross-sectional area of the diffuser and delivery pipelines are five times greater than the sum of the downstream diffuser hole areas to ensure that pressure drops do not exceed that required to provide a uniform flow distribution through the diffuser.

Destratification system. As it is illustrated in Figure 1*a)*, the destratification system for San Roque Reservoir uses seven deep and shallow diffusers, each made up of three perforated pipes strapped together and located side-by-side, anchored in concrete blocks (see Figure 1*b)*). To ensure minimal stirring of the reservoir sediments by the compressed air flow, the diffusers are located 1 m from the bottom. The deep diffuser is located at the maximum possible depth of the reservoir, in the channel near the dam, and its role it is to break down the seasonal thermocline. Regarding the shallow bubblers, they are located in the open basin in order to maximise the spatial extent of mixing, and the main purpose of these diffusers is to break down the diurnal thermocline.
The deep diffuser delivers 233 l/s of compressed air, through 100 clusters of 7 holes per cluster. It consists of one line, made up of five co-located pipes, each of 89 mm internal diameter and 925 m in length (Table 1). The shallow diffuser delivers 700 l/s of air, through 2750 clusters of 1 hole per cluster. It consists of six lines, with each line also made up five co-located pipes, each of 89 mm internal diameters and 925 m in length. The distance between plumes was chosen to minimise the amount of plume-plume interaction which reduces the efficiency of the system (Lemckert *et al*. 1993).
The deep diffuser requires one compressor capable of delivering 233 l/s of air at approximately 500 kPa for effective operation. The shallow bubbler requires three compressors, each capable of delivering 233 l/s at approximately 400 kPa at the start of the diffuser line.

Table 1. Destratification system design specification.

Bubbler System	**Shallow diffuser**	**Deep diffuser**
Design criteria		
Total airflow (L/s)	700	233
Cluster number	2750	100
Cluster spacing (m)	6	28
Air flow / cluster (L/s)	0.25	2.33
Length (m)	925	925
Diffuser holes		
Diameter (mm)	1.4	1.4
N^o holes / cluster	1	7
Flow per hole (L/s)	0.25	0.34
Diffiser inner diameter (mm)	89	89

Sampling methodology and data analysis

Reservoir monitoring began in October 2008. Measurements primarily focused on both the entire waterbody response to aeration system, and the near-field plume environment in 2011. During 2008 to present, transects were measured fortnightly to monthly at 12 sampling locations (Figure 1*a)*) using a HORIBA probe (conductivity, temperature, pH, DO and turbidity). In 2011, spatially high-resolution (1-2m) transects were performed across an individual plume of the diffuser located near the dam. A total of 21 profiles were measured, with the 0-m point being located above of the centre of the plume. The profiles were measured every 1.5 meters from 0 to 9 meters in either direction, then 3 meters from 9 to 21 meters.

RESULTS

Influence of destratification on far-field water temperature

Field measurement focused on the effects of the diffusers on the thermal stratification and circulation within the reservoir. Figure shows that operation of the destratifier that was activated by the end of October 2008 it helped to facilitate the mixing by weakening the thermal stratification as expected. The large-scale mixing of the reservoir only could occur as a result of the introduction of mixing energy from the atmosphere through a combination of wind stirring and heat loss. The smaller surface temperature values measured within the area near the bubbler system (Figure 2*b)*) in comparison with the larger values measured far from the diffusers (Figure 2*a)*) during the summer 2009, indicates that artificial destratification has been effective at avoiding diurnal stratification and reducing the surface to bottom temperature differential.

The effect of the system on dissolved oxygen concentrations can be seen in Figures 3. After activation, the OD concentrations increased at water column depth within the area of the diffusers (Figure 3*b)*).

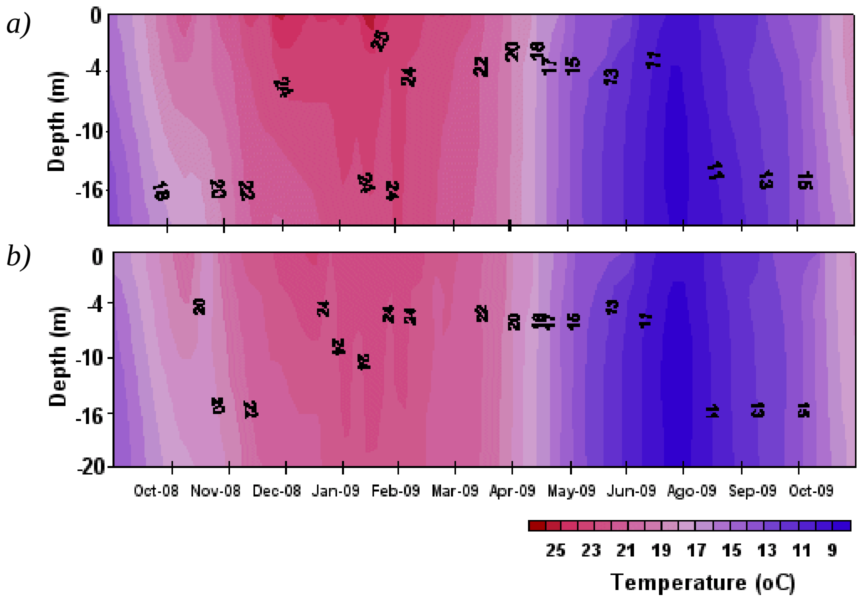

Figure 2. Temperature field data during years 2008 - 2009. *a)* Sampling station A: far from diffuser area, and *b)* sampling station B: in diffuser area.

Near field environment induced by the bubble plume

The collected data suggest that the area of influence of the destratifier is restricted to a narrow radial distance (of approximately 10 m) around the bubble-plumes during periods of strong stability (or thermal stratification). Figures and show typical high-resolution temperature and DO contour plots from February 2011. During artificial mixing, each cone-shaped rising plume of bubbles entrained ambient fluid from throughout the water column and carried it up to the water surface. At the surface, each plume extended out radially over a short distance of about 8 meters. The maximum speed at which the reservoir water propagated away from the plumes was estimated from field anemometer acoustic data and it was about 0,08 m/s close to the plumes, and it slowed to 0,04 - 0,01 m/s at about 1 km approximately.

The high resolution contour plot shown in Figure 4 suggests a turbulent plume, fairly heterogeneous in nature. The detrainment observed at 10 m of depth may be explained by plume water fallback from either detrainment at the top of the plume, detrainment along the rising plume (multiple detrainment), or a combination of both. Most probably, the air plume detrains most of the entrained water where the downward buoyancy dominated upward momentum flux about the 10 m of depth. The entrained fluid then sinks to its neutral buoyancy level before forming the lateral outflow in the left side of the plume. The lines superimposed on Figure 4 indicate the extend of the bubble core, which appears to spread only slightly. Further, measured data indicates an approximately Gaussian distribution as expected. The depression in the temperature isopleths and the higher DO that plunges almost to the reservoir bottom in the left side of the plume may be the result of local drawdown resulting from plume upflow.

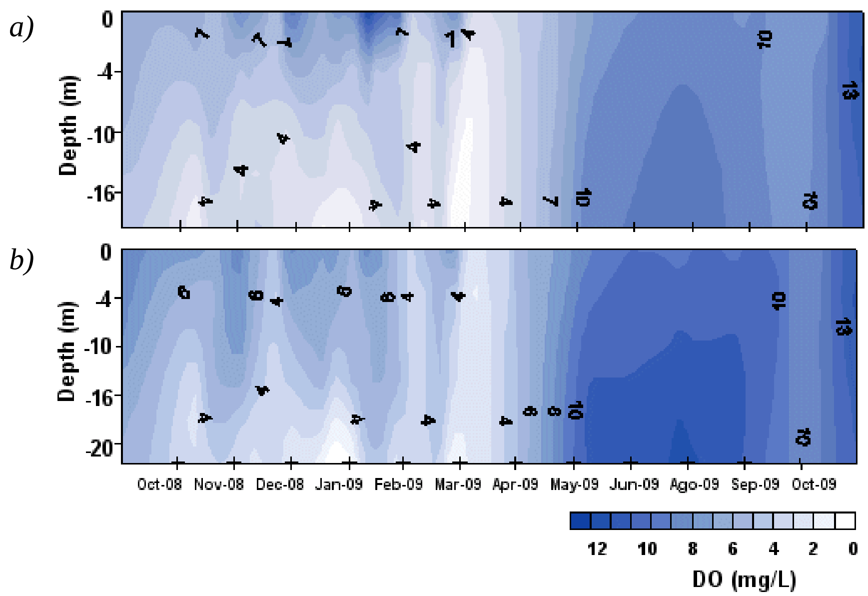

Figure 3. Measured DO during years 2008 - 2009. *a)* Sampling station A: far from diffuser area, and *b)* sampling station B: in diffuser area.

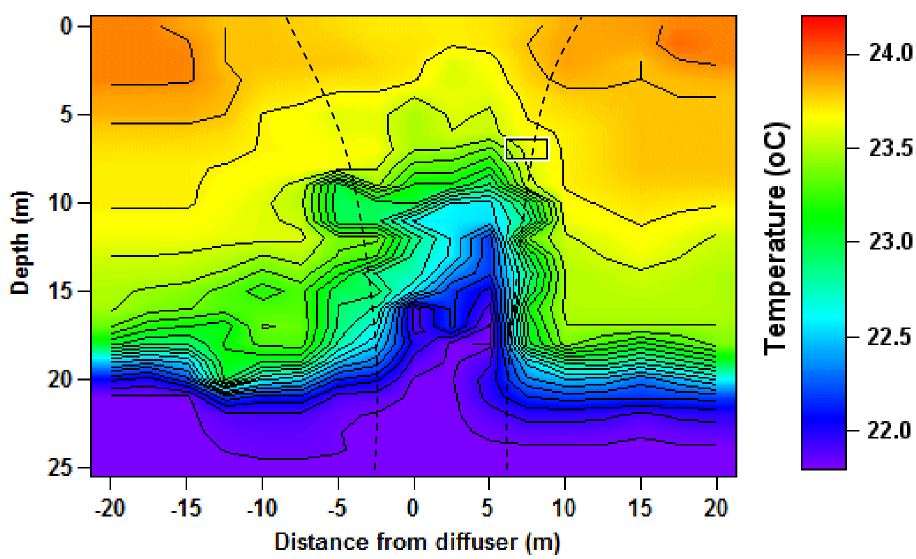

Figure 4. Temperature contour plot measured in February 2011 in San Roque Reservoir. The contours were interpolated from 21 profiles sampled along the centreline of the narrow area of the reservoir. The *x* axis zero point is located at the centre of the diffuser line.

Measured data shown in Figure 4 indicates that temperature is substantially lower than in the ambient reservoir water. The reason is that the plume initially entrains water from the anoxic and colder bottom layer and then rises to the surface. Under these conditions, the temperature (and other constituent concentrations) within the plume is governed by the initial conditions at the diffuser and entrainment of surrounding water.

Changes in Chl-*a* concentrations

The overall level of Chl-*a* in the reservoir did not differ significantly from that in the years before and after the start of destratification. Because of difficulties in completely destratifying the eutrophic layer a decrease in total phytoplankton biomass could not be achieved. Figure 5 shows chlorophyll concentrations in surface waters.

To further investigate the effect of artificial mixing on the reservoir, the three-dimensional hydrodynamic model ELCOM (Estuary, Lake and Coastal Model, see Hodges *et al*. 2000) coupled to the ecological model CAEDYM (Computational Aquatic Ecological Dynamic Model, Romero and Imberger 2003) was run for 120 days with the above bubbler system configured in the model. The destratification system was activated on the day 20 of the modelling, and run continuously for the duration of the simulation. From the above analysis, it was possible to predict the turn-over time for a reservoir that was mixed by the bubble plume system and the subsequent Chl-*a* for different setting bubbler configurations. Figure 6 shows simulation results suggesting that insufficient mixing can have extremely negative effects.

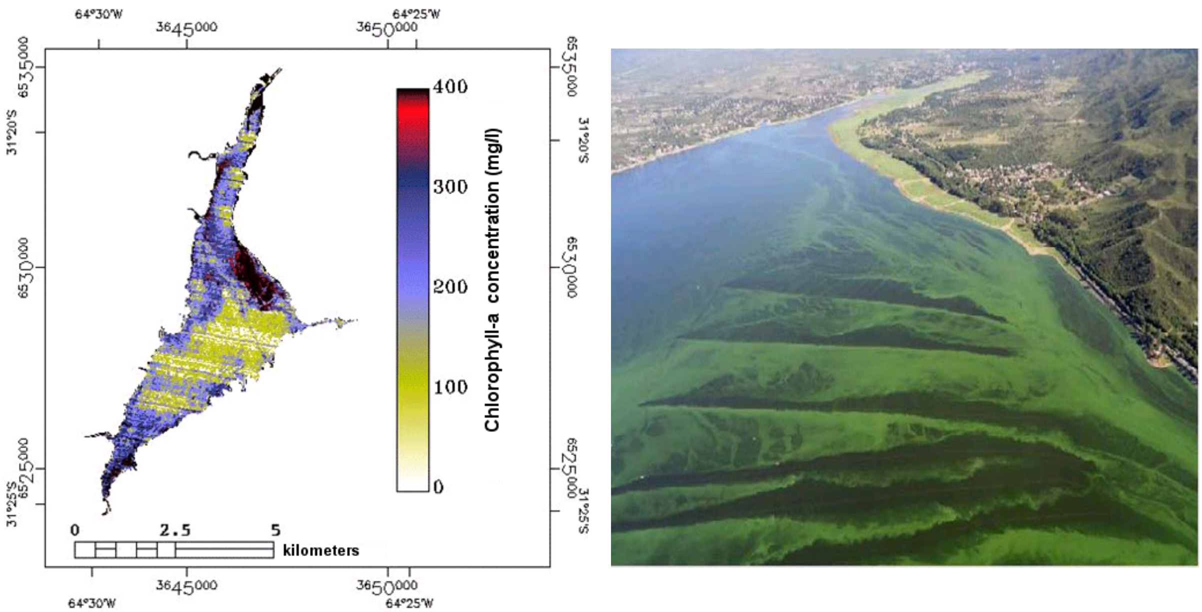

Figure 5. *a)* Chlorophyll concentration based on Landsat 5TM (16-Feb-2009). *b)* Aerial photo of San Roque Chlorophyll concentration during December 2010. Surface algaes concentration suggests the location and influence area of the six diffusers located in the open basin of the reservoir.

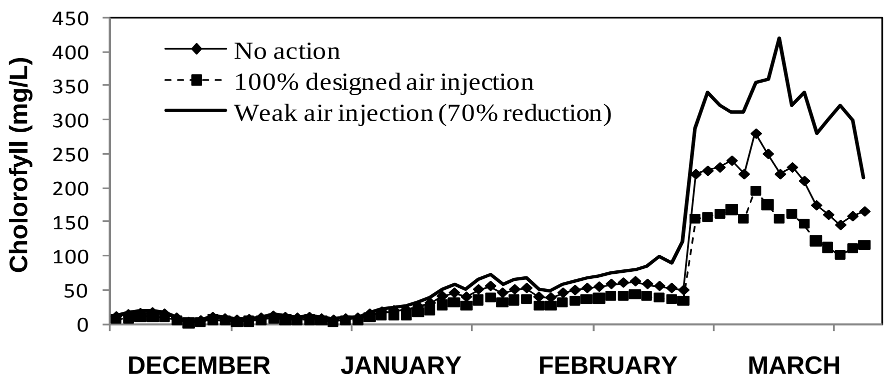

Figure 6. Simulation results showing the chlorophyll-a concentrations at the centre of the reservoir following different intensity of air injection.

CONCLUSIONS

Artificial destratification of San Roque reservoir has been effective at reducing the surface to bottom temperature differential and increasing dissolved oxygen concentrations at depth. While the operation of the destratifier has led to ‘destratification’ during the summer months, it has not been successful at fully ‘mixing’ the reservoir. This is evident by the presence of weak thermal gradients and a microstratification layer between 0 and 4 m. This, coupled with the significant increase in bottom temperatures during summer has resulted in the oxygen demand of the sediment being greater than the rate of replenishment. Hence, while operation of the destratifier has led to a significant increase in the average summer concentrations of dissolved oxygen at deeper waters, anoxic conditions are likely to persist at the sediment-water interface due to the increased oxygen demand. This narrow zone of anoxia may be sufficient to facilitate the release of dissolved constituents, providing a substantial source of bioavailable nutrients to the eutrophic zone during summer.

After activation of the system, field data indicates that a decrease in total phytoplankton biomass cannot be achieved because of difficulties in completely destratifying the eutrophic layer. Incomplete mixing and frequent desactivations of the system, they have also resulted in the transport of dissolved nutrients to the euphotic zone, further encouraging the growth of cyanobacteria. Overall, results demonstrated that artificial mixing may improve water quality; if improperly sized or operated, however, such mixing can also cause deterioration. Any disruption in aeration during the destratification process, for example, may result in an accelerate decrease of oxygen levels due to the higher hypolimnetic temperatures.

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