Effects of bubbling operations on a thermally stratified reservoir: implications for water quality amelioration

R. L. Fernandez, M. Bonansea, A. Cosavella, F. Monarde, M. Ferreyra and J. Bresciano

ABSTRACT

Artificial thermal mixing of the water column is a common method of addressing water quality problems with the most popular method of destratification being the bubble curtain. 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, requires analogous design criteria. In this paper, the influence of a bubble-plume is evaluated using full-scale temperature and water quality data collected in San Roque Reservoir, Argentina. A composite system consisting of seven separated diffusers connected to four 500 kPa compressors was installed at this reservoir by the end of 2008. The original purpose of this 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 modelling, this work demonstrates that thermal mixing by means of compressed air may improve water quality; however, if improperly sized or operated, such mixing can also cause deterioration. Any disruption in aeration during the destratification process, for example, may result in a reduction of oxygen levels due to the higher hypolimnetic temperatures. Further, the use of artificial destratification appears to have insignificant influence on reducing evaporation rates in relatively shallow impoundments such as San Roque reservoir.

Key words | bubble-plume, eutrophication, near-field, reservoir, stratification, water quality

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INTRODUCTION

Eutrophication of reservoirs as a result of intense riparian settlement within the semi-arid Central region of Argentina has contributed to a number of water quality problems such as algal and cyanobacterial blooms, reduced recreational aesthetics, hypolimnetic oxygen depletion, reduced transparency and fish kills.

Artificial thermal mixing 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 (see Helfer *et al.* 2011; Gafsi & Kettab 2012; and others). This method uses pipes with holes, porous hoses, or porous diffusers to produce a pumping compressed air-bubble column, 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 plume velocity. In stratified quiescent environments, 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 environment.

The overall goal of this air-bubble curtain is to sufficiently reduce, or prevent, the stratification so that the waterbody 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. Hence,

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as the design of artificial destratification systems is based on theoretical hydrodynamic principles, the reservoir modelling tools often used do not consider the full range of environmental variability, leading to inadequate energy production for complete mixing when applied in practice. For example, lake depth may limit the success of artificial destratification systems as was reported for the Chaffey Dam (Sherman *et al.* 2000). In this case study, the average depth was too shallow to keep cyanobacteria out of the eutrophic zone for periods long enough to reduce production through light limitation. Further, 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. However, destratification in some situations can have adverse impacts through eliminating coldwater habitats for fish and zooplankton, or distributing contaminants or nutrients from bottom areas with high concentrations into the entire water column.

This paper reviews the operational effectiveness of a compressed air destratification system that has been attempted in Argentina since October 2008 in San Roque reservoir, in Cordoba Province. The capacity of San Roque reservoir is 200 million m^3 and it is 25.5 m deep at top water level. In the absence of any artificial circulation, the reservoir stratifies mainly into two layers during the summer season (December to March). There is a warm epilimnion in the top 8 m of the reservoir, with temperatures ranging from 23 to 26 °C, which is a prolific algal growth layer. The bottom layer has much lower temperatures, and is oxygen deficient. As a result of nutrient inflow from the catchments, in combination with high ambient temperatures (~40 °C), the reservoir is periodically infested with blue-green algae. This results in water treatment problems in respect of taste and odour, and iron and manganese soluble salts. To abate such problems, air has been artificially circulated in the reservoir since 2008. In this context, based on a combination of full-scale temperature data, water quality measurements and remote sensing imagery analysis, this paper seeks to contribute to the understanding of the effects of a bubble destratification system on the mixing processes, water quantity and water quality amelioration of a deteriorated reservoir under strong anthropogenic pressure.

METHODOLGY

Study site

San Roque reservoir was constructed by damming the Suquia river in 1891. It is a reservoir with a medium depth of 17 m, length of 10 km, and a maximum width of 3.5 km (Figure 1(a)). Its maximum volume is 200 million m^3 and it covers an area of 16 km^2. The theoretical average retention time is 6 months. San Roque is a warm monomictic reservoir, experiencing thermal stratification during November to March. Under stratified conditions, oxygen depletion

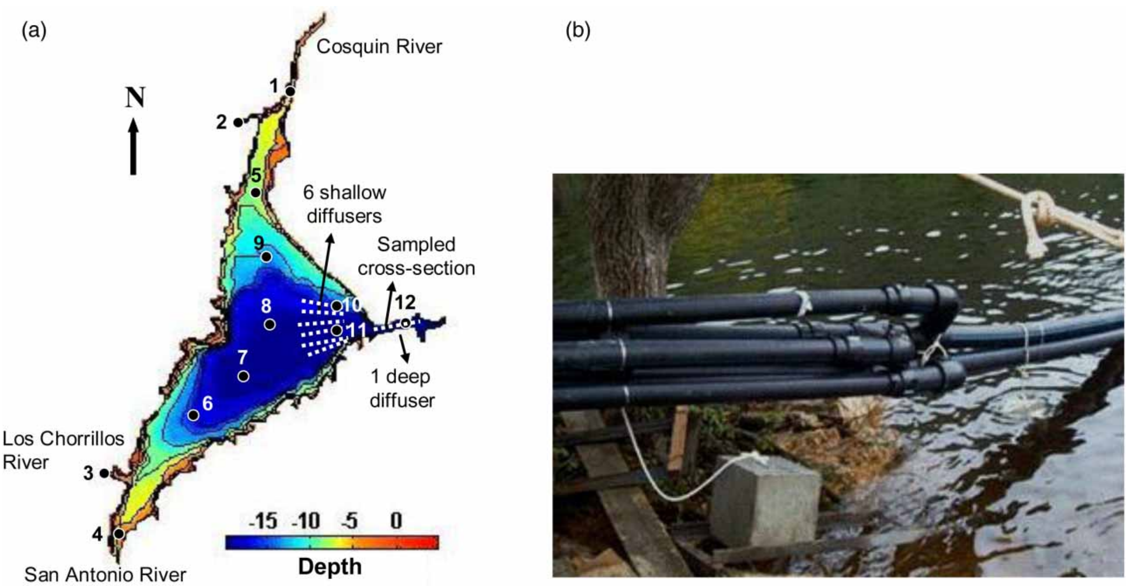

Figure 1 | (a) San Roque Reservoir bathymetry showing the twelve sampling stations (black dots), diffuser locations (dashed lines) and sampled cross-section. (b) Air supply pipes and anchor before being submerged into the reservoir water. The cross-sectional area of the diffuser and delivery pipelines 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.

within the hypolimnion is severe. Prior to installation of the destratification system, up to 40% of the lake volume experienced anoxia during the summer months (Helmbrecht 2002). The light is highly attenuated with depth, the maximum euphotic depth being restricted to the first 2–3 m.

Destratification system

As 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, i.e. in the channel near the dam, its' role being to break down the seasonal thermocline. Regarding the shallow bubblers, they are located in the open basin in order to maximize the spatial extent of mixing, the main purpose of these diffusers being to break down the diurnal thermocline.

The deep diffuser delivers 233 l/s of compressed air, through 100 clusters of seven 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 2,750 clusters of one hole per cluster. It consists of six lines, with each line also made up five co-located pipes, each of 89 mm internal diameter and 925 m in length. 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° holes/cluster	1	7
Flow per hole (l/s)	0.25	0.34
Diffuser inner diameter (mm)	89	89

Sampling methodology

Field measurements focused on both the entire waterbody response to the aeration system (long-term monitoring) and the near-field plume environment (short-term high resolution monitoring). To produce water column profiles, since 2008 long-term monitoring has been performed monthly at the 12 sampling locations indicated in Figure 1(a). A HORIBA probe equipped with five sensors (conductivity, temperature, pH, DO and turbidity) was used to characterize the response of the reservoir to the artificial mixing.

Complementary to this analysis, spatially high-resolution (1–2 m) transects were performed on 16 February 2011 across an individual plume of the diffuser located near the dam. Thus, in the selected cross-section indicated in Figure 1(a), a total of 21 profiles were measured with the 0 m point being located above the centre of the plume (or centre of the channel). Along the cross-section, temperature and DO profiles were measured every 1.5 m from 0 to 9 m in either direction from the centre, and then every 3 m from 9 to 21 m. As the purpose of this second experiment was to characterize the near-field plume hydrodynamics, it was important to exclude the effect of meteorological and hydrological conditions during these measurements. Accordingly, on 16 February 2011 the atmospheric temperature was about 28 °C at the time of the profiling (midday), precipitation did not occur during the previous days, total river inflow was about 584,000 m^3 while sampling was performed, and daily average wind velocity did not exceed 2 m/s. These records suggested that the weather while these experiments were performed was calm, which means the disturbance to stratification due to precipitation, river inflow and strong wind was minimal during the field experiment. Further, as the inflow rate was small and the water temperature of the rivers was higher than that at the surface of the reservoir (about 1 °C higher), river water might not intrude into the bottom of the water column.

RESULTS

Influence of destratification on far-field water temperature

Long-term measurements focused on the effects of diffusers on the thermal stratification and circulation within the

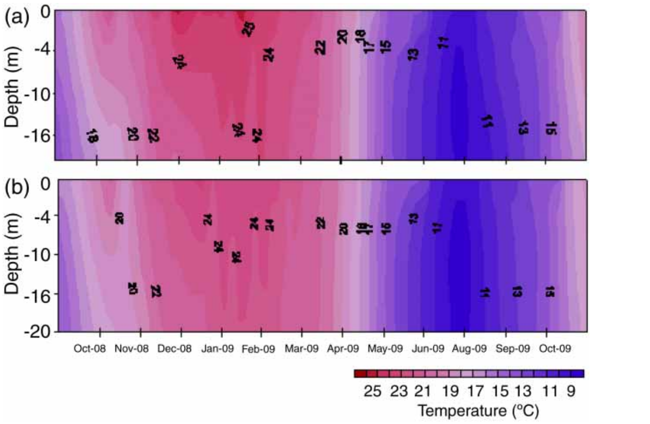

Figure 2 | Temperature field data during years 2008–2009. (a) Sampling station 8: relatively far from the diffuser area, and (b) sampling station 11: within the diffuser area.

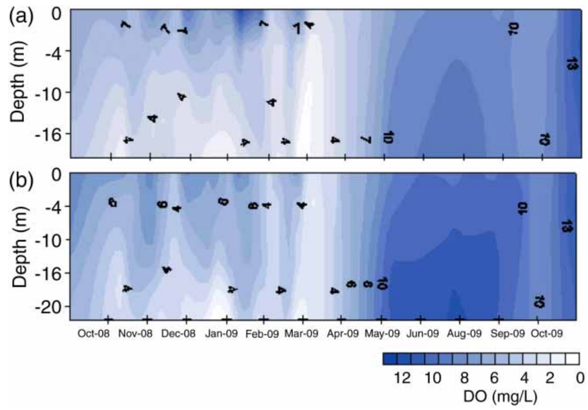

Figure 3 | Measured DO during years 2008–2009. (a) Sampling station 8: far from diffuser area, and (b) sampling station 11: within the diffuser area.

whole reservoir. As expected, Figure 2 shows that artificial mixing started by the end of October 2008 helped to weaken the thermal stratification of the water column, particularly at sampling station 11 (Figure 2(b)). Hence, the lower surface temperature values measured within this area near the bubbler system (Figure 2(b)) in comparison with the higher values measured far from the diffusers (Figure 2 (a)) during summer 2009, suggested that artificial destratification was effective at avoiding diurnal stratification, and in reducing the summer surface to bottom temperature differential (to an average summer range of 1.7 °C). Based on Figure 2, such a reduction was not sufficient to result in complete 'mixing' of the whole waterbody as the mixing induced by the air discharge was effectively damped by the ambient stratification in the far-field environment, the effects of the progressive destratification being restricted to the near-field of the diffusers.

Under the analysed diffuser configuration, the above results suggested that full circulation and mixing were not easy to achieve in San Roque reservoir, particularly near the surface in areas far from the diffusers. Because of these near surface thermoclines, algal blooms and other undesirable phenomena might result with time. On another note, it is expected that the large-scale mixing of the reservoir could then occur as a result of the introduction of mixing energy from the atmosphere through a combination of wind stirring and heat loss.

Alternatively, the effect of the destratification system can be seen in Figure 3 for DO concentrations at the same stations shown in Figure 2. Particularly, it can be noticed here that after air activation, the DO concentrations increased to over 12 mg/l within the area of the diffusers (Figure 3(b)) during the winter period (June – September).

Near field environment induced by the bubble plume

Figure 4(a) shows a typical high-resolution temperature plot measured on 15 February 2011. These measured data indicate that the plume temperature was substantially lower than in the ambient reservoir water. The reason is that the cone-shaped rising plume initially entrained water from the anoxic and colder bottom layer and then rose to the surface. Under these conditions, the temperature (and other constituent concentrations) within the plume could be governed by the initial conditions at the diffuser and entrainment of surrounding water. The detrainment observed at 10 m 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 detrained most of the entrained water where the downward buoyancy dominated upward momentum flux, at about 10 m depth. The entrained fluid then sunk to its neutral buoyancy level before forming the lateral outflow to the left side of the plume. The lines superimposed on Figure 4(a) indicate the extent of the bubble core, which appears to spread only slightly. The depression in the temperature isopleths that lightly plunges to the reservoir bottom on the left side of the plume may be the result of local drawdown resulting from plume upflow.

At the surface, the observed plume extended out radially over a short distance of about 8 m. The maximum speed at which the reservoir water propagated away from the plume was estimated from field anemometer acoustic data; 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 collected temperature data suggested that the area of influence of the

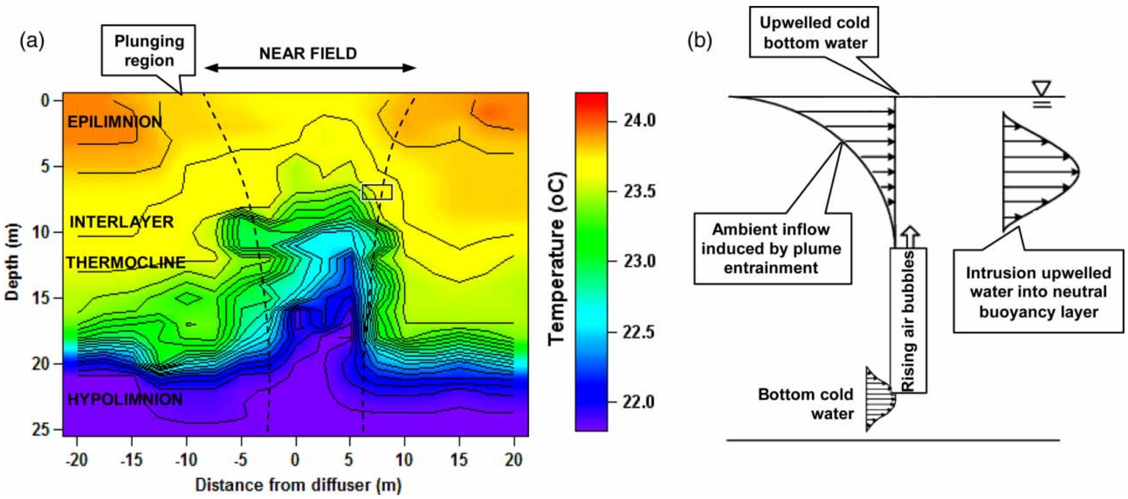

Figure 4 | (a) Temperature contour plot measured on 15 February 2011 in San Roque reservoir. The contours were interpolated from 21 profiles sampled along the narrow, cross-section of the reservoir close to the dam. The *x* axis zero point is located at the centre of the cross-section, above the diffuser line. (b) Simplified flow pattern observed from *in-situ* measurements. The intrusion of upwelled water occurred at a depth of about 8–10 m.

destratifier was restricted to a narrow radial distance (of approximately 10 m) around the bubble-plumes during the monitored day, in which the water column was characterized by strong stability or thermal stratification (with distinguishing epilimnion thermocline and hypolimnion layers).

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 (200–300 mg/l). The decrease in total phytoplankton biomass could not be achieved particularly due to difficulties in completely destratifying the eutrophic layer within the whole waterbody during summer, as discussed earlier (Figure 2). As an example, Figure 5 shows spatial chlorophyll concentrations in surface waters in February 2009 and December 2010 by using different visualization techniques.

Further analysis was carried out here to predict the effect of artificial destratification on these algal blooms by using the one-dimensional coupled hydrodynamics and water quality model DYRESM-CAEDYM (Patterson & Imberger 1989; Makler-Pick *et al.* 2011). These numerical codes have already been successfully validated in San Roque reservoir in

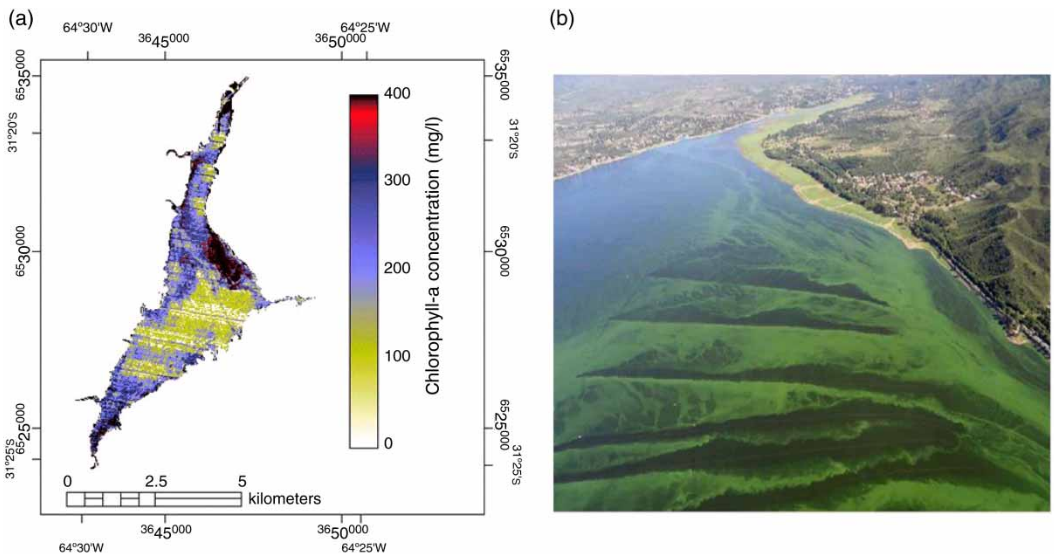

Figure 5 | (a) Chlorophyll concentration based on Landsat 5 TM (16 February 2009). (b) Aerial photo of San Roque chlorophyll concentration on December 2010. Surface algae concentration suggests the location and influencing area of the six diffusers located in the open basin of the reservoir. (Photograph courtesy of N. Rivero)

previous studies (see for example Antenucci *et al.* 2003; Hidalgo *et al.* 2009). The bubbling mixing subroutine incorporated into DYRESM is based on the plume model described by McDougall (1978), with the air plume entraining water from each layer as it passes through them as a result of the integration of equations for mass, momentum, and buoyancy. The stratification through which the plume rises is not confined to being linear, but rather it is the simulated density profile from the previous time-step. Hence, to give insight into the reservoir hydrobiological conditions, the DYRESM-CAEDYM model was run for 130 days (from 10 November 2008 to 20 March 2009) using the initial temperature profile measured on 10 November 2008 and with the configured San Roque bubbler system as summarized in Table 1. The coupled model was set-up to run DO, nutrients, suspended organic and inorganic solids, and four phytoplankton groups: (a) chlorophytes (nearly neutrally buoyant green algae, e.g. *Scenedesmus*), (b) cyanobacteria (buoyant blue-green algae, e.g. *Microcystis aeruginosa*), (c) diatoms (with a constant settling rate, e.g. *Melosira*), and (d) dinoflagellates (motile dinoflagellates, e.g. *Ceratium hirundinella*).

The destratification system was activated on day 10 of the modelling and run continuously for the duration of the simulation. Input to the simulation included weather parameters, lake morphometry, outflow data and inflow rates. Figure 6 shows the meteorological inputs for DYRESM during the 130 days of simulation; mean daily values were used for input. Figure 7 shows that the calibrated model reproduced very well the observed magnitude of water temperatures and DO variations at the monitoring station 8 in the centre of the reservoir.

Overall, numerical results allowed prediction of the turnover time for a reservoir that was mixed by the bubble plume system and the subsequent Chl-*a* concentrations for different settings of bubbler configurations. For example, in operation and during the destratification process, the water temperature within the hypolimnion increases. Any disruption then in the aerators may result in a reduction of oxygen levels due to these higher hypolimnetic temperatures. In this context, Figure 8 illustrates results for Chl-*a* concentrations at station 8 for three scenarios: (a) no aeration, (b) aeration at projected flow rate (see Table 1), and (c) aeration at a 70% reduced air flow rate. Hence, Figure 8 clearly suggests that a reduced air-flow rate, or insufficient mixing, can have extremely negative effects on phytoplankton biomass. During reduced air-flow rate or partial destratification, the top 4–5 m of the water column was excluded from the mixing, thereby forming a warm unmixed surface layer. This warm surface layer provided good conditions for phytoplankton growth; because phytoplankton was not mixed into the deeper aphotic layers, reduction of phytoplankton growth by light limitation could not be achieved. Further, the reduced airflow rate reduced also the influence area of the diffusers, limiting the whole mixing of the reservoir.

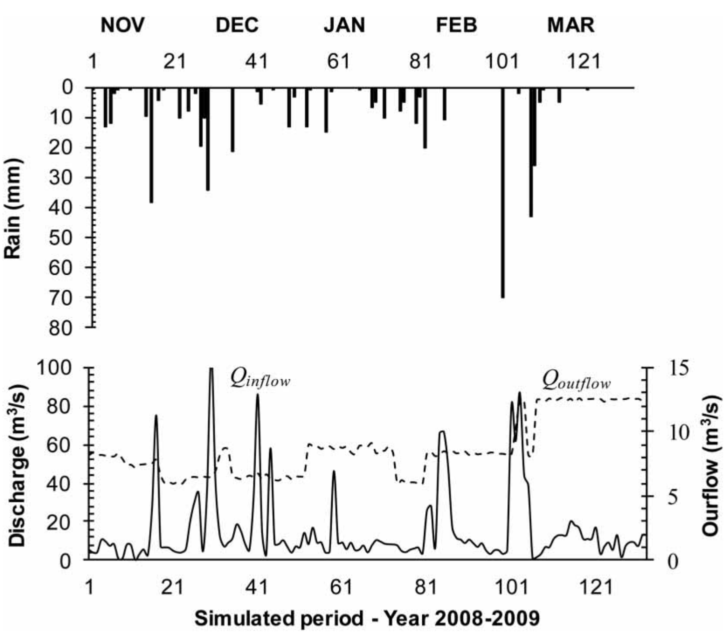

Figure 6 | Rainfall and hydrological data for San Roque Reservoir for 130 days of simulation. (Period 10 November 2008 to 20 March 2009)

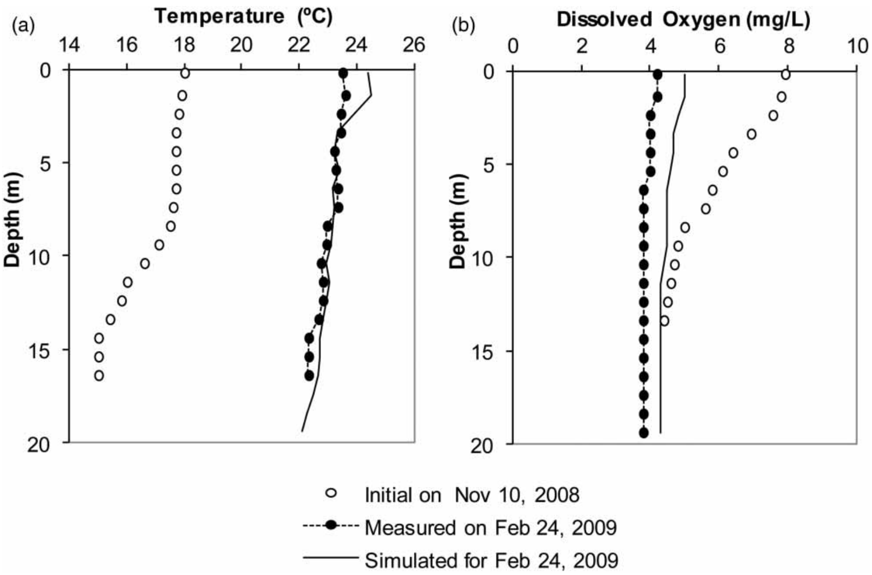

Figure 7 | Mixing and DO patterns of reservoir at the initial time of the simulation (10 November 2008) and after 105 days of destratification operation (on 24 February 2009). Shown are measured and simulated (a) temperature and (b) DO concentration profiles for central station 8.

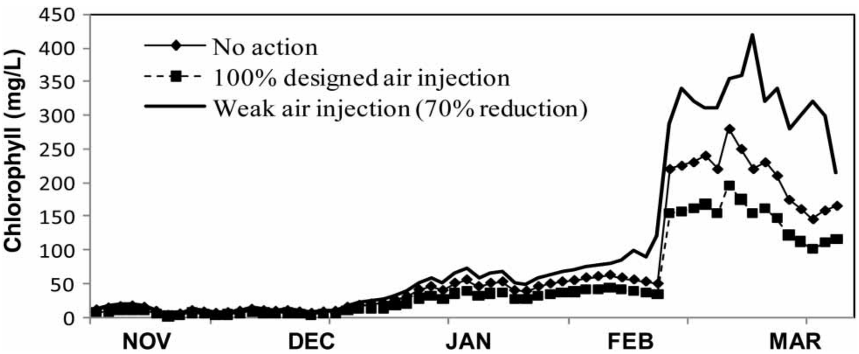

Figure 8 | Simulation results showing the chlorophyll concentrations at the centre of the reservoir following different intensity of air injection.

Variation in evaporation rates

As an alternative to the water temperatures shown in Figure 2 for two different monitoring stations, the Landsat images of Figure 9 show the water surface temperature in the reservoir under the influence of aeration (Figure 9(a) on 24 February 2009) and with the destratification system turned off (Figure 9(b) on 15 March 2010). Significantly, relatively lower water surface temperatures (~1–1.5 °C) can be observed in Figure 9(a) within the bubbler system area.

Given the additional concern regarding influences of destratification on the evaporation process at San Roque reservoir, an attempt was made to estimate daily evaporation rates. The one-dimensional model DYRESM was used to simulate the mixing due to artificial aeration and the resultant evaporation rates. As the effectiveness of a destratification system in reducing evaporation is expected to the existence of cold temperatures in the hypolimnion associated with warm temperatures in the epilimnion, a condition like this would be expected in the spring and summer (and probably the beginning of autumn). Hence, for the above simulated period (November to March) Figure 10 compares results for two different simulations: a baseline simulation, in which no destratification system was operated, and a simulation in which the reservoir was under continuous artificial aeration conditions. The evaporative reduction within the simulated period in comparison with the baseline evaporation varied from 2.8 to 4.4%. Figure 10 shows evaporation rates (mm/day) when aeration was not

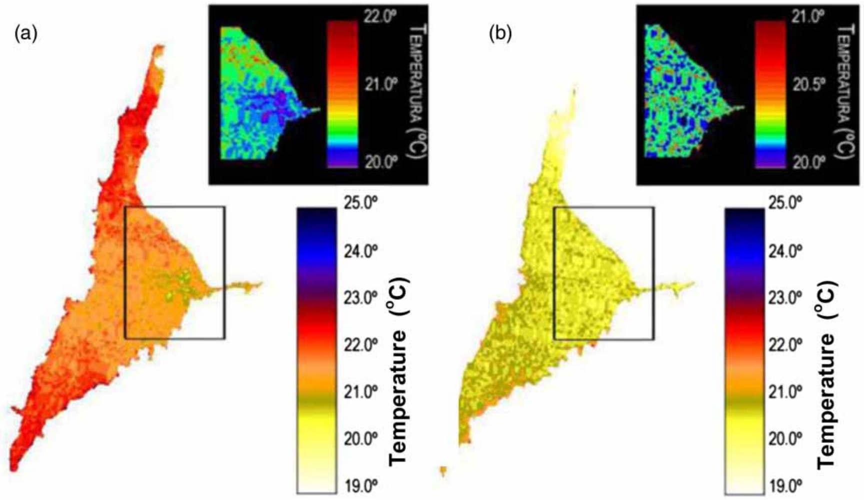

Figure 9 | Reservoir water surface temperature. (a) During destratification operation (image on 24 February 2009). (b) After the suspension of destratification (image on 15 March 2010).

operating (E_{off}) and the evaporation differences resulting when considering the action and non-action of the diffusers ($E_{off} - E_{on}$), expressed in m^3/s. Further, the average reservoir surface temperature for the simulated period was 21.9 °C which dropped to 20.8 °C with aeration. The reduction of surface temperature was evidenced more clearly for days of high temperatures and in the deepest areas of the reservoir (in agreement with Figure 9(a)).

CONCLUSIONS

Artificial destratification of San Roque reservoir has been effective at reducing the surface to bottom temperature differential and increasing DO concentrations at depth. Particularly, the study found that the destratification system did not result in large-scale mixing of the reservoir, although the aerators reduced stratification intensity, which might result in a greater chance of wind induced mixing.

Further, field and simulated data indicated that a decrease in total phytoplankton biomass could not be achieved because of difficulties in completely destratifying the eutrophic layer. Here, incomplete mixing within the whole reservoir resulted in the transport of dissolved nutrients to the euphotic zone, further encouraging the growth of cyanobacteria. Overall, numerical results demonstrated that artificial mixing may improve water quality; if improperly sized or operated, however, such mixing when insufficient, can also cause deterioration. Any disruption in aeration during the destratification process, for example, may result in a reduction of oxygen levels due to the higher hypolimnetic temperatures.

Lastly, the implementation of diffusers as a technique to reduce evaporation in this shallow, medium-sized reservoir could not be considered as an efficient tool for alleviating

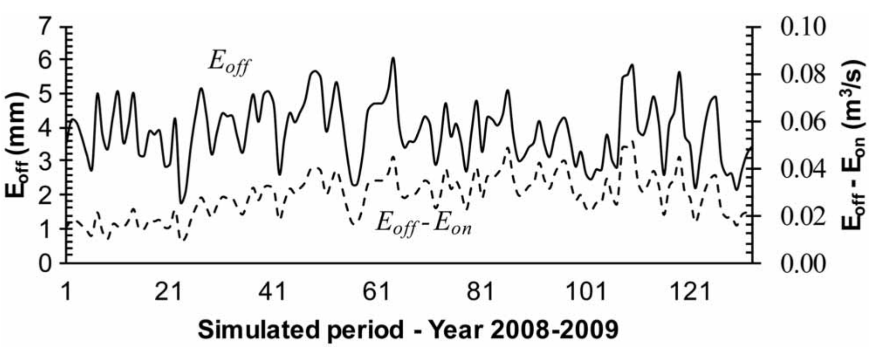

Figure 10 | Reservoir water surface temperature. (a) During destratification operation (image from 24 February 2009). (b) After the suspension of destratification (image on 15 March 2010).

the pressure of climate change in San Roque reservoir; that efficiency might increase with the reservoir depth (i.e. colder waters at the bottom) and ambient temperatures (i.e. tropical areas).

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