Assessing the effectiveness of air-bubble plume aeration in reducing evaporation from farm dams in Australia using modelling

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Abstract

This paper aims to assess the effectiveness of artificial destratification by air-bubble plumes in reducing evaporation from farm dams in Australia. A one-dimensional model was applied to simulate the change in water temperature and evaporation rates of a real farm dam in Queensland under aeration conditions. Results show that destratification systems can reduce surface temperature, but the highest reduction in evaporation for the studied reservoir would be only 2.5%. The main conclusion is that it is unlikely that the technique will be feasible for small farm dams, given the high costs involved with the operation of an aeration system and the small quantity of water saved through evaporation reduction. The results also indicate that the technique may be effective for reservoirs that experience long periods of accentuated thermal stratification, such as large, deep dams, in which the mixing process would lead to higher reductions in surface temperature and, consequently, in evaporation rates.
Keywords: DYRESM, thermal stratification, water aeration, evaporation, water temperature, destratification.

1 Introduction

Australian farm dams' capacity is approximately 7000 GL (7 x 10^9 m^3), representing 9% of the total water stored across the country. It is estimated however that 40% of the volume stored is lost every year due to the high rates of evaporation in agricultural areas in New South Wales and Queensland (Craig *et al.* [1]). Extremely high radiation and air vapour deficits make these areas experience evaporation rates that can surpass 2000 mm per year. As a

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consequence, the shortage of water leads to either, reduction in crop production or, when feasible, the necessity of building additional storage.

Therefore, conserving the water in existing storages is deemed as one of the most economical means of guaranteeing the water supply in Australia. Reducing evaporative losses is particularly desirable for several reasons: i) no additional transportation, pumping or collection expenses associated with the saved water; ii) no decrease in water quality or additional costs with water treatment; and iii) no risk and cost involved in developing a new supply (Cooley [2]).

For a long time, Australia has been developing and studying different mechanisms for reducing evaporation from farm dams. Most of the techniques, however, have been shown not to be effective, such as windbreaks (Helfer *et al.* [3], Helfer *et al.* [4]), to be excessively expensive, such as physical covers (Yao *et al.* [5]) and modifying the dam's shape to minimize surface area (McJannet *et al.* [6]), or to impose potential risks to the water quality, such as the use of chemical and physical covers (McJannet *et al.* [7], Yao *et al.* [5]).

One technique deserving further investigation is aeration by air-bubble plumes (or air diffusers) which has been suggested in the literature as a potential mechanism for reducing evaporation (e.g. Koberg and Ford [8]), but little work has been done with the intention of quantifying the change in evaporation under application of this technique. The potential of aeration in reducing evaporation is related to the change in water temperature brought about by the mixing device. The principle is that cold bottom water is lifted up by the air injected at the bottom of the lake. At the surface, this water mixes with warm water, reducing the temperature, and consequently, evaporation rates. Given this principle, the technique may only be effective in lakes that experience thermal stratification, since there has to be a difference between the temperatures of the bottom and the surface waters.

In this present study we apply a one-dimensional model, DYRESM (Imberger and Patterson [9]), to a stratified farm dam in Australia to study the effects of aeration by air-bubble plumes on evaporation.

2 DYRESM

DYRESM (acronym for DYnamic REservoir Simulation Model) is a 1-D vertical heat transfer model used for the prediction of the distribution of temperature, salinity and density with depth and time for lakes and reservoirs of medium size and is in wide use. Examples of its application can be found in Imberger and Patterson [9], Patterson *et al.* [10], Ivey and Patterson [11], Hollan *et al.* [12], Schladow and Hamilton [13], Hornung [14], Moshfeghi *et al.* [15] and Hipsey [16].

DYRESM operates on the principles of conservation of mass, momentum, heat, kinetic energy and salt. The hydrodynamic part includes algorithms for surface heat, mass and momentum transfers, mixed layer dynamics, mixing in the hypolimnion and water exchange through inflows and outflows.

The model is based on a Lagrangian layer scheme in which the reservoir is represented by a series of adjoining horizontal layers that vary in thickness and number. At each time step, as inflows and outflows enter or leave the reservoir, the affected layers expand or contract and those above move up or down to accommodate the volume change. Mixing and surface layer deepening are modelled by amalgamation of layers, with layer properties redistributed according to conservation of mass and energy.

The surface heat, mass and momentum exchange comprise the primary driving mechanisms for DYRESM. The surface exchanges include heating due to short-wave radiation penetration into the lake and the fluxes at the surface due to evaporation, sensible heat, long-wave radiation and wind stress (see Imberger and Patterson [9] or Imerito [17] for further details on the equations used in DYRESM). For the evaporative flux at the surface, DYRESM employs the bulk aerodynamic formula:

$$E = -\frac{0.622}{P}\rho_a \lambda C_E U\left(e_a - e_s\right). \tag{1}$$

where E is the latent heat flux, P is the atmospheric pressure, ρ_a is the air density, λ is the latent heat of evaporation, C_E is the bulk aerodynamic transfer coefficient (=1.3E-3), U is the wind speed, e_a is the vapour pressure in the air and e_s is the saturation vapour pressure, which is a function of the surface water temperature.

Meteorological data required by the model include incident long and short wave radiation, rainfall, air temperature, humidity and wind speed. Other inputs include inflow and outflow properties (volume, temperature and salinity), initial profiles of temperature and salinity in the lake and a depth-area relationship of the lake.

DYRESM also incorporates a sub-routine to model water mixing by destratification devices, such as impellers and air diffusers. For air diffusers, the algorithm is based on a simple, single core plume whose motion is determined from three differential equations of conservation of mass, momentum and buoyancy (Patterson and Imberger [18], Imerito [17]). This sub-routine requires a number of destratification devices operating in the reservoir, device type (i.e., air diffuser or impeller), draft tube length and diameter (for impellers), height and number of ports (for diffusers), volume flow rate of air (for diffusers) and volume of water (for impellers).

3 Methodology

3.1 Case study

The model DYRESM was applied to a large farm dam located in Queensland, Australia to study the effects of artificial destratification on evaporation. Logan's Dam (27°34′26″S, 152°20′26″E, Figure 1) has a storage capacity of 0.7 GL, a full storage surface area of approximately 17 hectares and a maximum depth of 6.5 m. All data sets, including meteorological, morphological and outflows (pumping), were provided by the South-East Queensland Urban Water Security Research Alliance, which has been monitoring the dam since August, 2009, for

Figure 1: Aerial view of the selected farm dam (Source: Google Earth).

evaporation study purposes. Inflows were estimated by performing a volume balance on the water body. Mean daily values for all inputs were adopted.

The period chosen for the simulations, based on available and consistent data, was from 29/09/2009 to 27/01/2010 (121 days). Some DYRESM parameters were first calibrated for Logan's Dam. For validation of the calibrated model, the surface, middle and bottom temperature, as well as the temperature of the entire profile, were compared with the corresponding field data. A comparison between predicted and observed lake water level was also conducted. Predicted values for the overall lake temperature (Figure 2a) led to a mean absolute error of 0.79°C, a mean relative error of 2.4% (-19 to 10%) and a coefficient of determination, R^2, of 0.93 in comparison with field measurements. For the temperature of the surface only (Figure 2b), the mean absolute error was 0.88°C, the mean relative

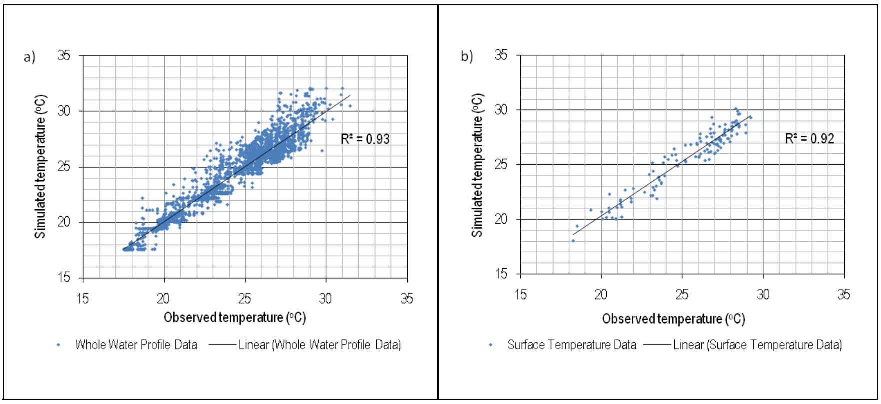

Figure 2: Simulated water temperatures in Logan's Dam for the period 29/09/2009–27/01/2010 in comparison with observed temperatures. a) Whole profile data. b) Surface data.

error, 2.7% (-9.5 to 6.4%) and the coefficient of determination, 0.92. These indexes indicate a suitable adjustment of the model. Figure 3 shows the field temperature for the whole profile and the result of the simulated water temperature.

Although not strong, Logan's Dam experienced thermal stratification from the beginning of November until the end of the period of study, interspersed with some periods of none or of weak stratification (Figure 3). The daily average surface temperatures varied from 18.5°C in 29/09/2009, to 29.6°C in 27/01/2010. Considering daily average, the strongest thermal gradients occurred in the end of November, with drops of up to 2.5°C m^{-1} in the metalimnion.

The hypothetical scenarios for the present study consisted of artificial destratification by air diffusers of different configurations being used intermittently throughout the 121 days of simulation. Different configurations were tested in order to find the design of the destratification system that provides

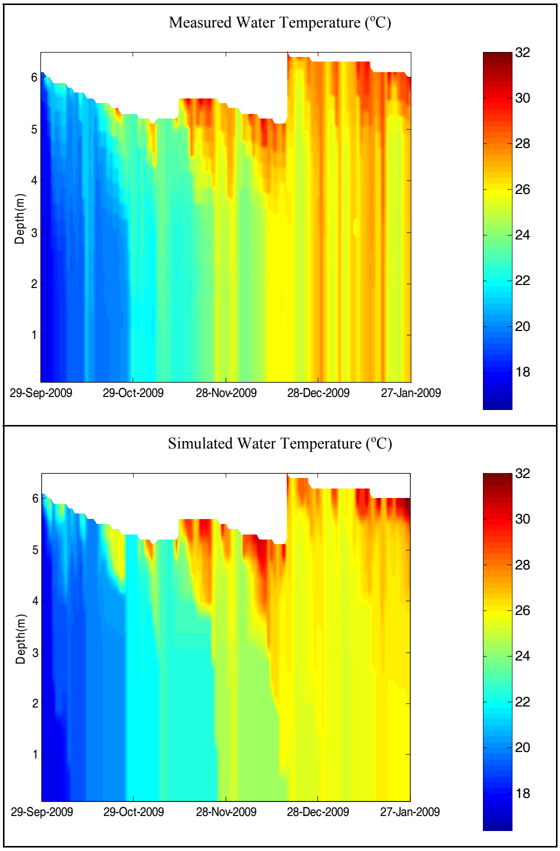

Figure 3: Measured and simulated water temperature in Logan's Dam from 29/09/2009 to 27/01/2010.

maximum evaporation reduction. The number of diffusers operating in the dam varied from 1 to 4, and number of ports on each diffuser, from 10 to 960. Total air-flow rate per diffuser varied from 0.003 to 0.096 m^3/s. The diffusers were assumed to be placed at the bottom of the lake. A total of 169 simulations were run and evaporation and water temperature were noted for analysis as described below.

4 Results and discussion

4.1 Evaporation

The total evaporation for the whole period of simulation (121 days) and for all destratification designs is presented in Figure 4. Each graph represents different numbers of diffusers operating in the lake (i.e., 1, 2, 3 or 4). The air-flow rates presented on the x-axis are per diffuser and at the ambient pressure at the level of the diffuser. Each line shows the number of ports per diffuser. The ranges of air-flow rates pumped into the lake and number of ports were selected according to the feasibility for the circumstances of the study domain.

The baseline evaporation calculated by DYRESM for the period between 29/09/2009 and 27/01/2010 from Logan's Dam is 635 mm and evaporation under aeration conditions varied from 635 to 619 mm depending on the

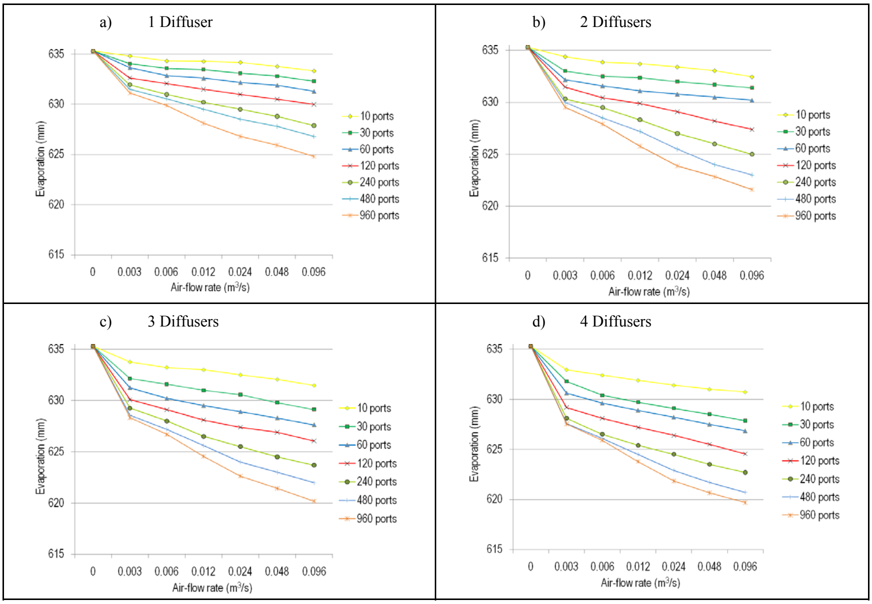

Figure 4: Evaporation from Logan's Dam for the period 29/09/2009 to 27/01/2010 under different aeration system designs. Baseline evaporation is represented by the 0 m^3/s air-flow rate.

number of diffusers, the maximum evaporation reductions occurred at the maximum air-flow rate (0.096 m^3/s) and at the maximum number of ports (960). However, these reductions vary from only 1.7% (-10.5 mm in 121 days), in the 1-diffuser scenario, to only 2.5% (-15.7 mm in 121 days) in the 4-diffuser scenario. So, as the number of diffusers increases, the reduction in evaporation also increases, but these changes are just minor. This tendency is also confirmed by Figure 5a. For 1, 2, 3 and 4 diffusers, each with 10 ports and operating at an air-flow rate of 0.096 m^3/s (dashed lines), the reductions are 0.3, 0.4, 0.6 and 0.7%, respectively, in comparison with the baseline scenario. For 960 ports (solid lines) and same air-flow rate (0.096 m^3/s), the reductions found are 1.7, 2.2, 2.4 and 2.5%, respectively for 1, 2, 3 and 4 diffusers.

Figure 5b shows the variation in evaporation with the number of ports for 1 (dashed lines) and 4 (solid lines) diffusers. It is clear that evaporation decreases as the number of ports on each diffuser increases, due to a more efficient water mixing. For 4 diffusers and 10 ports on each, operating at an air flow rate of 0.096 m^3/s, evaporation reduction is 0.7%. When the number of ports is increased to 960, evaporation reduction increases to 2.5%. Therefore, out of all configurations tested, the maximum reduction in evaporation occurs for 4 diffusers, each operating at an air-flow rate of 0.096 m^3/s and 960 ports. However, it is important to point out that this decrease is only 2.5% (15.6 mm in 121 days).

An ‘unrealistic’ scenario with 10 diffusers, 1000 ports and an excessively high air-flow rate was also simulated in order to find what the lake evaporation would be under a situation of fully-mixed water. Under this circumstance, the total evaporation was 618 mm. This indicates that further mixing in the lake through other destratification designs other than those already tested would result in more consumption of energy but with no further decrease in evaporation.

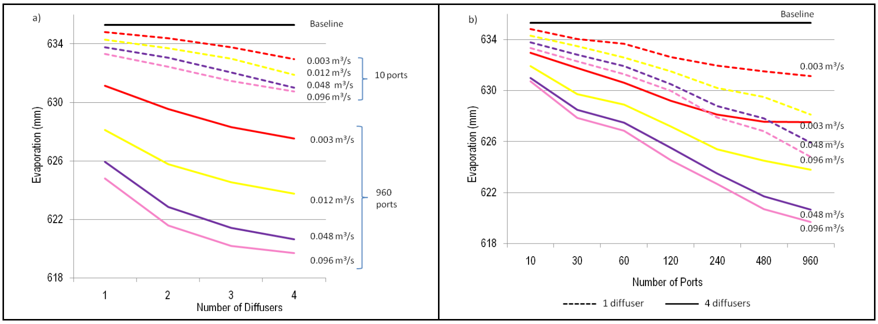

Figure 5: Relationship between evaporation from Logan’s Dam and a) number of diffusers and b) number of ports per diffuser.

4.2 Temperature

Figure 6 shows the surface temperature variation for the baseline simulation and for the simulation under strong aeration (i.e. 4 diffusers, 960 ports and air-flow rate = 0.096 m^3/s). The figure also shows the difference between bottom and surface temperatures for both scenarios. The average surface temperature is 26.7°C for the whole period of simulation for the baseline scenario. For weak aeration (1 diffuser, 10 ports and air-flow rate = 0.003 m^3/s) the average surface temperature for the period of simulation is also 26.7°C and for strong aeration (4 diffusers, 960 ports and air-flow rate = 0.096 m^3/s), 26.6 °C, indicating that there was no significant difference in the average surface temperature between the simulations. However, the graph in Figure 6 shows that the surface temperature for the strong aeration scenario is sometimes higher and sometimes lower than the baseline temperature. The bottom set of lines in the graph of Figure 6 shows the difference between surface and bottom temperatures for both scenarios (baseline and strong aeration). It is clear that the aeration reduces the difference of temperature between surface and bottom, making the profile more homogenous. However, when it comes to surface temperature, the aeration process does not have a significant effect on temperature reduction. From the graph, it can be interpreted that the temperature of the surface is lowered after aeration whenever there is a significant difference between surface and bottom waters under natural conditions (e.g. beginning and end of October, middle-end of November, beginning of December and almost the whole month of January). In these cases, the process of aeration efficiently brings cold water from the bottom up to the surface, decreasing the temperature, and therefore, evaporation rates. On the other hand, the surface temperature after aeration is increased whenever there is no considerable difference between surface and bottom temperatures. This indicates that when the temperature of the lake is naturally homogeneous under normal circumstances, the aeration process increases the heat stored in the dam, impeding the dissipation of heat into the atmosphere. Consequently, in conditions of homogeneous water temperature, evaporation in the aerated scenario is higher than in the baseline. This is confirmed by Figure 7, which shows the change in surface water temperature and the change in

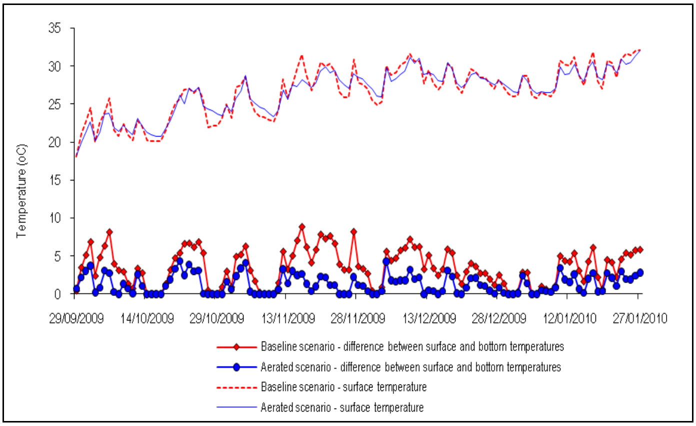

Figure 6: Effects of strong aeration on surface water temperature and on the difference between surface and bottom waters of Logan's Dam.

evaporation after aeration (again, for the case of 4 diffusers, 960 ports and 0.096 m^3/s of air per diffuser). The bars show the temperature of the surface after aeration, in comparison with the natural condition, and the blue line shows the evaporation, also as a percentage of the baseline values. Thus, evaporation is increased when surface temperature increases and reduced when surface temperature reduces.

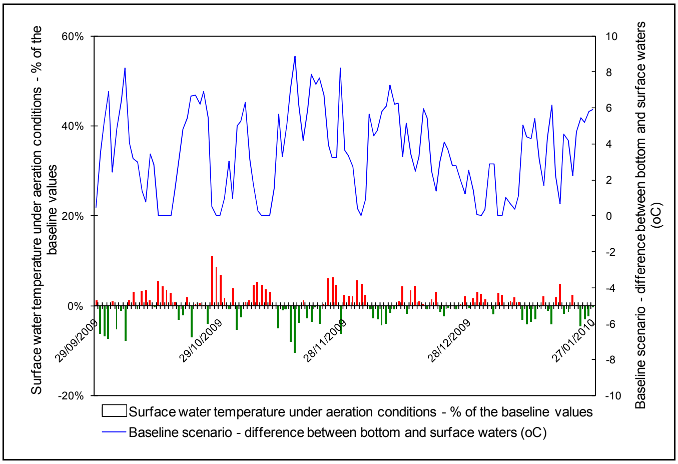

Figure 7: Effects of strong aeration on surface water temperature of and evaporation from Logan's Dam.

Therefore, the effectiveness of aeration in reducing evaporation will depend on the existence of a difference between bottom and surface temperatures. If a lake experiences thermal stratification during a long period, aeration will probably have a positive effect on evaporation reduction during this period. However, in a small, shallow lake like Logan's Dam, which may experience periods of strong thermal stratification interspersed with well-mixed periods (due to natural mixing), success of artificial mixing in reducing evaporation will only be achieved if the periods of decrease in surface temperature prevail over the periods when surface temperature is increased. For the studied reservoir, periods of strong thermal stratification were longer than periods of well-mixed water, leading to a positive effect of aeration on evaporation reduction. The extent of this effect is related to the design of the destratification system, but the maximum reduction would be only 2.5%. This maximum evaporation reduction is achieved using a high energy-consuming design. Figure 8 shows the relationship between various destratification system designs and the costs per unit of saved water for Logan's Dam. The graphs also show the costs involved to produce water by desalination. It can be considered that any destratification system design, whose costs per unit of saved water is higher than that for desalination, are not cost-efficient. Therefore, only a few designs would result in cheaper water costs than that produced water by desalination.

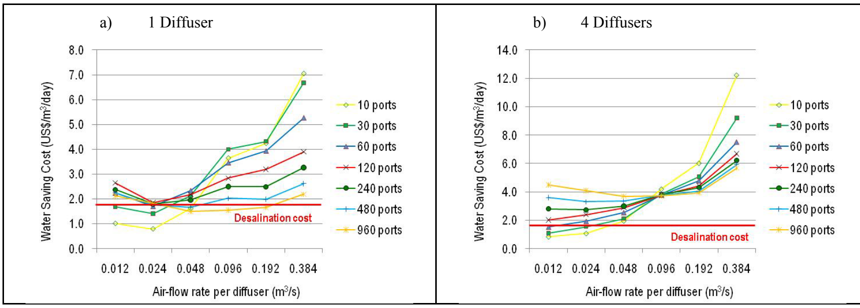

Figure 8: Water saving costs for different destratification system designs for Logan's Dam (2 and 3 diffuser graphs were omitted).

5 Conclusion

The efficiency of intermittent air-bubble plume aeration in reducing evaporation from open waters is a function of the occurrence of periods of strong thermal stratification in the lake. Whenever there is a significant difference between bottom and surface temperatures, the technique successfully reduces surface temperature and evaporation. However, during periods of well-mixed water column the process of aeration may increase the heat stored in the water, leading to an increase in evaporation rates. The effectiveness of the technique in reducing evaporation will, therefore, depend on the circumstances of each reservoir. For Logan's Dam, for example, it is unlikely that the method will bring benefits in terms of evaporation reduction due to the high relation between the costs to install, operate and maintain an aeration system and the water saved. Nevertheless, the model DYRESM has shown to be a potential tool to predict the change in water temperature and to estimate evaporation rates from open waters under aeration conditions. However, calibration and validation of the model under artificial aeration conditions is still necessary to assure an accurate prediction and will be the basis of further research.

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