Artificial destratification for reservoir evaporation reduction: is it effective?

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Short running title:

Destratification for evaporation reduction

Abstract: The aim of this study was to assess the effectiveness of artificial destratification by air-bubble plumes in reducing evaporation from reservoirs. DYRESM was used to model the evaporation rates and thermodynamic behavior of a temperate reservoir in Australia under a number of combinations of destratification designs and operating conditions. The designs comprised various numbers of ports and air-flow rates per port. The operating conditions involved continuous operation and various intermittent operating strategies. Three reservoir depths were considered: 6.5, 11.5 and 16.5 meters, characterizing ‘shallow’, ‘medium’ and ‘deep’, respectively. The results showed that, provided thermal stratification develops in a reservoir (which was the case for the

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‘medium’ and ‘deep’ reservoirs), artificial destratification is able to reduce surface temperatures and evaporation rates. Due to the larger volume of cold water at the bottom, deeper reservoirs can derive greater benefit from the use of these systems. After being raised to the surface by the air injected through the destratification system, the cold water from the bottom will help reduce the surface temperatures. Conversely, shallow lakes, due to their typical homothermous regime, are unlikely to benefit from these systems, as these reservoirs lack a source of abundant cold water at the bottom. Despite this, the reductions in evaporation from deep reservoirs can only be modest. The maximum reduction was only 2.9% for a deep lake (16.5 meters), using an energy-intensive destratification system. It was concluded that the use of destratification systems for reservoir evaporation reduction are not warranted because of the modest water savings achieved.

Keywords: air-bubble plumes, DYRESM, evaporation, hydrodynamic modelling, lake, reservoir, vertical mixing, water balance, water temperature

1. Introduction

The world is facing growing pressure regarding water resources due to the increasing strain imposed by population growth, economic development, extreme drought and climate change. The pressure on water resources is being felt more intensively in arid and semi-arid locations where water is even more scarce (Bouwer, 2000; Maestre-Valero et al., 2013). This scarcity is drawing increasing attention to the development of water-saving cost-effective and reliable approaches. Reducing evaporation from reservoirs could effectively help arid and semi-arid countries to overcome water scarcity (Martinez Alvarez et al., 2008; Gallego-Elvira et al., 2013).

In Australia, evaporation from reservoirs is regarded as the most adverse factor contributing to loss of water. It is estimated that 40% of the volume stored in Australian

reservoirs is lost each year due to high evaporation rates (Craig et al., 2005). Evaporation can often exceed 2000 mm per year in most areas in Australia (Department of Natural Resources and Mines, 2005). Additionally, climate change has been posing a significant threat to water availability in Australian reservoirs as there is a growing body of climate evidence in support of increases in Australian air temperatures, with concurrent increases in evaporation rates (CSIRO & BoM, 2007). In South-East Queensland, where this study was conducted, an investigation showed that annual evaporation will be approximately 8% higher than the current long-term average annual evaporation around the year 2040, and 15% higher around the year 2080 (Helfer et al., 2012a).

For decades, arid and semi-arid countries such as Australia have been investigating and developing mechanisms for reducing evaporation from reservoirs and thus contributing to water security. Most of the techniques however, have been shown either not to be effective, as in the example of windbreaks (Helfer et al., 2009a; 2009b); to be excessively expensive, as in the example of floating covers and shade-cloth covers (Martinez Alvarez et al., 2009); to impose potential risks on water quality, as in the example of chemical and physical covers (Yao et al., 2010); or to be difficult to implement at field scale, as in the use of chemical covers (Barnes, 2008).

Artificial destratification by air-bubble plumes (the injection of air through a diffuser placed at the bottom of a lake) is one technique suggested in the literature as a potential mechanism for reducing evaporation from reservoirs (Koberg & Ford, 1965; Helfer et al., 2011a; 2011b; 2012b). Destratification devices are tools to mix or circulate water vertically in a reservoir. Their primary purpose is to prevent thermal stratification, which is frequently associated with substantial hypolimnetic oxygen depletion (Johnson, 1984; Beduhn, 1994). Hypoxia in lakes and reservoirs stresses aquatic life, threatens fish populations, and reduces water quality (Bertone et al., 2015). The potential of this

technique for controlling evaporation loss lies in cooling the temperature of surface waters through vertical mixing (Helfer et al., 2011b). When in operation, destratification systems allow the colder hypolimnion water to mix with the warmer surface water, reducing surface temperatures and, consequently, evaporation rates. Based on this theory, it follows that there has to be significant temperature stratification in a lake for these systems to be effective in reducing relative evaporation. To date, however, only a few studies have focused on the use of air-bubble plumes to reduce evaporation from reservoirs. Helfer et al. (2011a) suggested that the technique could be more effective in deep reservoirs due to the development of a pronounced thermal stratification profile, where high differences between surface and bottom water temperatures develop. However, further studies were required to better quantify the achievable evaporation reduction.

In this context, the aim of the current study was to undertake a comprehensive study on the effect of artificial destratification systems on evaporation reduction from reservoirs. Reservoir depth, number of destratification ports (diffuser holes), air-flow rates, and operation strategies of destratification systems were investigated and correlated with evaporation rates. Three reservoir depths (6.5, 11.5 and 16.5 meters, characterizing a ‘shallow’, ‘medium’ and ‘deep’ lake), with varying numbers of air diffuser holes, and varying air-flow rates per hole were studied. A number of operation strategies were also analyzed, including, for example, destratification systems in continuous operation over the period of simulation, as well as in various intermittent operation schedules, such as in weekly and monthly cycles. The investigations were all conducted with the use of modelling and simulation using the one-dimensional model DYRESM, as described in the following section.

2. Materials and Methods

2.1. DYRESM

DYRESM (Imberger & Patterson, 1981; Imerito, 2010a; 2010b) is a one-dimensional hydrodynamic model used for the prediction of the vertical distribution of temperature, salinity and density in reservoirs, at daily and sub-daily time-steps. For over 30 years, this model has been successfully applied to a range of water bodies with various morphologies and climatic conditions to predict water quality parameters (e.g. Shiati, 1991; Hamilton & Schladow, 1997; Moshfeghi et al., 2005; Perroud et al., 2009; Weinberger & Vetter, 2012; Anderson et al, 2014; Lehman, 2014; Hetherington et al., 2015) as well as evaporation rates (Hipsey, 2006; Helfer et al., 2011b; McGloin et al., 2014). By comparing a number of one-dimensional lake models, Perroud et al. (2009) found that DYRESM is one of the best models to reproduce the variability of the water temperature profiles in lakes and reservoirs. As a one-dimensional model, DYRESM assumes that vertical variations in density, temperature and salinity are more important than horizontal variations, as these are rapidly relaxed by horizontal advection and convection due to the restoring force of stratification being greater than the disturbing force of the wind.

The main input data in DYRESM are the depth-area relationship of the studied lake, daily or sub-daily meteorological data (incident short-wave radiation, rainfall, air temperature, air vapour pressure, wind speed, and either net long-wave radiation, incident long-wave radiation or cloud cover fraction), daily inflows (and inflow temperature and salinity), daily outflows, and an initial profile of lake temperature and salinity (from which DYRESM derives the initial water depth). The model is based on a Lagrangian layer scheme in which the reservoir is represented by a series of adjoining horizontal layers of uniform properties that vary in thickness within user-defined limits. 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.

The mechanisms to heat and cool a lake are shortwave radiation (penetrative and non-penetrative), longwave radiation and sensible and latent heat fluxes. The surface mass fluxes include rainfall and evaporation. The wind field in DYRESM drives the surface layer shear and the latent and sensible heat fluxes. Wind stress, shortwave radiation, heat penetration, latent heat, sensible heat and longwave radiation are the main inputs of energy for mixing and stratifying the lake. Mixing and surface layer deepening are modelled by amalgamation of layers, based on a criterion of available kinetic energy and required potential energy for mixing any two layers. Three mixing mechanisms are considered in the model: stirring, in which wind energy is transferred to the surface layer; convective overturn, in which the energy is provided from a reduction in potential energy due to dense water sinking to a lower level; and shear, in which kinetic energy is transferred from the upper to the lower layers. The mixing algorithm involves computing the available energy for mixing two layers, and comparing this with the required energy for mixing these layers. Mixing (amalgamation of layers) occurs when there is enough energy for mixing, in which case the excess energy is transferred and used for the mixing of deeper layers.

The sensible and latent heat fluxes are calculated by mass transfer models. Importantly, the evaporative flux at each time-step is calculated as a function of wind speed and humidity deficit:

$$E = C_E \rho U (q_s - q_a) \quad (1)$$

where E is evaporation ($\text{kg m}^{-2} \text{s}^{-1}$), ρ is the air density (kg m^{-3}), C_E is the bulk aerodynamic transfer coefficient for a measurement height of 10 m ($=1.3 \times 10^{-3}$, Fischer et al., 1979; Brutsaert, 1982), U is the wind speed (m s^{-1}), and q_a and q_s are the actual and saturation

specific humidities, respectively (kg kg^{-1}). The saturation specific humidity is a function of the uppermost water layer.

One important feature in DYRESM is a sub-routine to model artificial water mixing based on destratification devices, such as impellers and air diffusers (bubble plumes). The artificial mixing algorithm has been successfully validated with field data in many instances (eg, Imteaz & Asaeda, 2000; Lewis et al., 2001; Imteaz et al., 2009). For air diffusers (the artificial mixing mechanism simulated in this study, which consists of a device through which air is injected at the bottom of the reservoir), the algorithm is based on a simple, single core plume, assumed to be circular and non-interacting (McDougall, 1978). The motion of this plume is determined from three differential equations of conservation of mass, momentum and buoyancy (Patterson & Imberger, 1989). To model the bubble plume artificial mixing, DYRESM uses the same layer discretisation used in the main routine, with the bubble plume entraining water from each layer as the air bubbles travel through them. As the bubble plume rises, the effective buoyancy anomaly between plume and ambient water decreases as entrained water lowers the plume density, at the same time that the ambient water density decreases with height as a result of thermal stratification. In the layer where the buoyancy anomaly becomes zero or negative, the water in the plume is ejected horizontally into the reservoir, and the plume model resumes. The model assumes that this detrained water immediately routes back to its neutrally buoyant level, without further entrainment.

The bubble plume mixing algorithm requires the following input variables: the depth of the diffuser in the water (h), the total air-flow rate at the diffuser level (Q_T), the number of destratification devices in operation, and the number of ports per device. In each time step, the total air-flow rate is divided by the number of ports to obtain the air-flow rate per port (Q_B). All calculations are then computed on a 'per port' basis.

The bubble plume model initialises by computing the buoyancy flux (B) resulting from the injection of air at the level of the diffuser (Q_B):

$$B = gQ_B \quad (2)$$

where g is the gravity. The flow rate of entrained water at the level of the diffuser (Q_P) is calculated as:

$$Q_P = \alpha \frac{6\pi}{5} b_l \gamma B^{1/3} \Delta Z_B^{5/3} \quad (3)$$

where α is the entrainment coefficient ($= 0.083$ - List, 1982; Milgram, 1983), b_l is a constant ($= 4.7$), γ is the plume aspect ratio (plume radius to plume length, assumed to be constant and equal to 0.1), and ΔZ_B is the layer thickness at the diffuser depth. For subsequent layers, the flow rate of air (Q) is computed as a function of the change in pressure head, which increases the air-flow rate due to bubble expansion:

$$Q_i = Q_{i-1} \left(\frac{H_{i-1}}{H_i} \right)^{0.71} \quad (4)$$

where $(i-1)$ refers to the layer immediately below, and H is the pressure head at the level of the layers. Only for the second layer from the diffuser layer, Q_{i-1} is replaced by Q_B . The combined buoyancy flux due to air bubbles and entrained water is calculated as:

$$B_i = gQ_i - g \left(\frac{\rho_{0i} - \rho_i}{\rho_{0i}} \right) Q_P \quad (5)$$

where ρ_{0i} is the density of the ambient water in the current layer, and ρ_i is the density of the plume. The flow rate of the entrained volume in layer i is:

$$Q_{P_i} = \alpha \frac{6\pi}{5} b_l \gamma B_i^{1/3} (z_i^{5/3} - z_{i-1}^{5/3}) + Q_{P_{i-1}} \quad (6)$$

where z is the depth of each layer.

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190 When the combined buoyancy flux becomes zero or negative, the entrained water is
191 ejected from the plume and it is assumed to fall to its neutrally buoyant level
192 instantaneously. The plume characteristics are then reset, and the air continues to rise and to
193 entrain water again.

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195 **2.2. Study area and data collection**

196 A reservoir used for irrigation of crops, located in South-East Queensland,
197 Australia, was used to study the effects of artificial destratification on evaporation. Logan’s
198 Dam (27°34’26’’S, 152°20’27’’E, altitude 88 m, Figure 1) has a storage capacity of 0.7
199 hm³, a full storage surface area of approximately 17 hectares and a maximum depth of 6.5
200 m. The reservoir is roughly rectangular in shape with dimensions of approximately 480 m x
201 350 m.

202 A comprehensive 2-year investigation on open water evaporation was conducted by
203 the Urban Water Security Research Alliance (UWSRA) (www.urbanwateralliance.org.au)
204 from 2009 to 2011 at Logan’s Dam. As part of this investigation, measuring equipment
205 items, including flow meters, water level sensors, thermistor chains and weather stations,
206 were installed at the reservoir to measure inflows, outflows, water levels, water
207 temperatures, and to monitor atmospheric conditions. A thorough description of the
208 equipment used and measurements taken at Logan Dam’s is provided in McGloin et al.
209 (2014) and McJannet et al. (2013a,b). All data sets needed to calibrate, validate and run the
210 model DYRESM in this study, including initial water temperatures, lake morphology
211 (elevation vs surface area relationship), external forcing daily data for solar radiation, wind
212 speed, air temperature and rainfall, outflows and inflows were obtained from the UWSRA
213 investigation.

Figure 1. Aerial view of the agricultural reservoir investigated in the current study (from Google Earth) and its location in Australia. Location of centre of reservoir: 27°34'26''S, 152°20'27''E. Surface area: 17 hectares (170,000 m²).

2.3. Model calibration and validation for water temperatures

DYRESM was calibrated based on its ability to reproduce measured values of water temperature in Logan's Dam. The model performance was tested by undertaking regression analyses between daily temperature measurements and daily temperature outputs from the model. The calibration was implemented manually by using the error minimisation method (Perroud et al., 2009; Weinberger & Vetter, 2012). The period chosen for calibration was 29/09/2009 - 06/01/2010 (100 days), covering a significant part of spring and summer seasons, and a validation was undertaken over summer and autumn, during the period 07/01/2010 - 11/04/2010 (95 days). The model was calibrated with respect to the parameter light extinction coefficient. The light extinction coefficient influences the thermodynamics of the lake through the varying water column heat absorption, but no measured data for this parameter was available for Logan's Dam. A mean annual, depth averaged value was assumed for the simulations, following similar studies (e.g. Hetherington et al., 2015). Different values were tested, ranging from 0.3 to 2.0 m⁻¹, with 1.3 m⁻¹ yielding the best match between simulated and measured water temperatures. This is a realistic value, since the lake is relatively shallow and turbidity is high (Oliver et al., 2000).

2.4. Model validation for evaporation rates

In the current study, the data collected by the UWSRA investigation, including rainfall, reservoir water levels, outflows and inflows, were used to determine observed daily evaporation rates by performing a water balance of the water storage. The water balance approach is a technique employed to estimate changes in water level by taking into

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241 account all the inputs and losses from a reservoir in a given period of time. The use of this
242 method to determine evaporation rates has been successful in a number of other
243 evaporation studies (eg, Abtew, 2001; Gibson, 2002). In the current study, the inputs for the
244 water balance model included daily inflows and direct rainfall. The reservoir losses
245 included daily outflows, evaporation and leakage. The water balance equation was
246 rearranged to determine the unknown daily evaporation rates from Logan’s Dam.

247 The water balance method for the determination of daily evaporation rates required
248 the specification of an estimate for the leakage term, since this parameter was not measured
249 on site. There have been several studies in which leakage losses have been determined for
250 Australian man-made reservoirs. For example, Craig (2006) determined leakage losses for
251 four reservoirs, comparing modelled evaporation rates with evaporation rates calculated
252 using the water balance method. The leakage loss term was determined as being something
253 between 1.0 and 2.0 mm day⁻², depending on the choice of the evaporation model.
254 McJannet et al. (2013a) compared evaporation rates from Logan’s Dam estimated by water
255 balance using two leakage loss terms (1.0 and 2.0 mm day⁻¹) with evaporation rates
256 measured with scintillometry. It was found that a leakage loss of 1.0 mm day⁻¹ would
257 overestimate evaporation rates from Logan’s Dam, whereas a leakage loss of 2.0 mm day⁻¹
258 would underestimate it. It was suggested that an optimal fixed leakage value for Logan’s
259 Dam would be something between the two aforementioned leakage rates (McJannet et al.,
260 2013a). Following this suggestion, in this study, we assumed a constant leakage loss of 1.5
261 mm day⁻¹ in the water balance model.

262 An indirect validation was also performed comparing the daily evaporation rates
263 estimated by DYRESM with daily evaporation rates estimated with a model proposed by
264 McGloin et al. (2014; 2015) for Logan’s Dam. Their model predicts eddy covariance
265 measurements for latent heat and has the form:

$$LE_{EC} = 27.91u(e_s - e_a) + 18.34 \quad (7)$$

where LE_{EC} is the approximated measured latent heat flux (W m^{-2}), u is the wind speed at 2.4 m height (m s^{-1}), e_s is the saturation vapour pressure at water temperature (kPa) and e_a is the vapour pressure of the air (kPa).

The evaporation rates calculated through both the water balance model and the latent heat model (Eq. 7) were subsequently compared with the daily evaporation rates estimated by the model DYRESM for Logan's Dam to evaluate the model's performance.

2.5. Scenarios, simulations and assumptions

The shallow lake scenario in this study represented the real situation, in which the maximum water depth at the deepest section of the reservoir is 6.5 m and the maximum surface area is 17 hectares (Figure 1). This is the scenario for which DYRESM was calibrated and validated. Hypothetical scenarios, with maximum depths of 11.5 m and 16.5 m, with 17 hectares of surface area, composed a medium lake scenario and a deep lake scenario, respectively.

In all three scenarios, the initial water depth was set as the maximum depth, and the initial water temperature, uniform throughout the profile, at 17.8°C (as measured in the field for the real case scenario).

The baseline simulations for each scenario consisted of the absence of any destratification system operating in the reservoir. Then, simulations with a destratification system operating continuously throughout the 195 days of study were simulated. The destratification system consisted of one air diffuser laid at the bottom of the lake with varying number of ports and air-flow rates. The air-flow rates injected through this diffuser into the water varied from 0.001 to $1.0 \text{ m}^3 \text{ s}^{-1}$, and the number of ports on each diffuser

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varied from 1 to 40. Table 1 summarises the simulations undertaken using continuous artificial destratification.

Table 1. Summary of the simulations with the artificial destratification system operating continuously over the period of study.

Following the results from the simulations provided in Table 1, the most effective systems were then selected for further evaluation of their operational strategies, including intermittent operation modes and operation in monthly and weekly cycles.

After the simulations were performed, evaporation rates from all simulations were noted for analyses. The differences in evaporation rates between destratification conditions and normal conditions (baseline simulations) provided an indication of the effectiveness of the destratification techniques in reducing evaporation. Analyses were then performed to determine the optimum combination of air-flow rate, number of ports and operational strategy that provided maximum evaporation reductions.

3. Results and Discussion
3.1. Observed meteorological conditions

Figure 2 shows a time series of the surface meteorology of Logan’s Dam for the simulation period (29/09/2009 – 11/04/2010), which covered spring, summer and autumn seasons. For reference, in Australia, the spring months are September, October and November; summer months are December, January and February; autumn months are March, April and May; and winter months are June, July and August.

Daily average shortwave solar radiation was 253 W m^{-2} , with the highest values concentrated in January 2010 (summer). The lowest shortwave radiation values occurred in the first week of March 2010 (autumn). The average air temperature for the entire period

was 24.1°C and ranged between a minimum of 16.2°C and a maximum of 30.3°C. The hottest period was the second week of December 2009 (summer), in which the average temperature was 28.5°C. The coldest period was the second week of October 2009 (spring). The average daily wind speed was 2.8 m s⁻¹, with a maximum of 6.1 m s⁻¹. For 90% of the time winds were less than 4 m s⁻¹. The average relative humidity was 67%, and the average vapour pressure deficit was 1.0 kPa, ranging from 0.2 to 2.4 kPa. Total rainfall was 365 mm in the period of simulation. Rainfall was mostly concentrated between the last week of January 2010 and the first week of March 2010, when 269 mm rainfall was registered.

Figure 2. Average daily shortwave solar radiation, air temperature, wind speed, vapour pressure deficit and total daily rainfall at Logan's Dam throughout the study period. For reference, in Australia, the spring months are September, October and November; summer months are December, January and February; autumn months are March, April and May; and winter months are June, July and August.

3.2. Model calibration and validation for water temperatures

3.2.1. Calibration period - 29/09/2009 to 06/01/2010 (100 days)

Figure 3 shows the measured and modelled water temperatures in Logan's Dam. The coefficient of determination (R^2) for the adjustment, considering 100 days of measured data, was 0.91, the root-mean-square error (RMSE) was 0.7°C, the mean relative error between simulated and field measurements (NRMSE) was 1.6% and the mean bias error (MBE) was -0.39°C. These indices demonstrate that the model provides a satisfactory representation of the real temperatures.

Figure 3. Isotherms for Logan’s Dam during the calibration period (29/09/2009 to 06/01/2010). This period covers the spring months of October and November, and the summer month of December and part of January. a) Measured data. b) Modelled data using DYRESM.

Since surface temperature is the most important variable in the calculation of evaporation (refer to Equation 1 for the evaporation model used in DYRESM), it is crucial that the temperature of the surface of the lake be modelled with a high level of accuracy. Figure 4 shows a strong correlation ($R^2 = 0.96$) between modelled and measured surface water temperatures for the 100 days of calibration. The regression equation for theoretical surface temperature values against observed values had a slope that was nearly equal to 1, indicating that the model predicts surface temperatures with high accuracy. The root-mean-square error was 0.57°C, and the mean bias error was virtually zero (-0.02°C).

Figure 4. Relationship between daily averages of measured (x-axis) and modelled (y-axis) surface water temperatures for the calibration period. The solid line indicates the regression equation, and the dashed line represents the 1:1 line.

3.2.2. Validation period - 07/01/2010 to 11/04/2010 (95 days)

Figure 5 shows the model’s performance for the validation period (07/01/2010 to 11/04/2010). The model performed as well as in the calibration period, with a coefficient of determination equal to 0.94, a root-mean-square error equal to 0.4°C, a mean relative error between simulated and field measurements equal to 1.10% and a mean bias error equal to -0.02°C.

Figure 5. Isotherms for Logan's Dam during the validation period (07/01/2010 to 11/04/2010). This period covers the summer months of January and February, and the autumn month of March and part of April. a) Measured data. b) Modelled data using DYRESM.

Figure 6 shows a strong correlation ($R^2 = 0.97$) between modelled and observed daily surface water temperatures for the 95 days of validation. The regression equation for theoretical surface temperature values against observed values had a slope equal to 1.02, indicating no tendency for either underestimation or overestimation of surface temperatures by the model. The mean bias error was virtually zero (0.02°C) and the root-mean-square error was 0.40°C . These results are in accordance with the results from a parallel study conducted at Logan's Dam, in which a strong agreement ($R^2 = 0.97$, $\text{RMSE} = 0.97^\circ\text{C}$) between hourly surface temperature measurements and hourly surface temperatures predicted with DYRESM was found (McGloin et al., 2014).

Figure 6. Relationship between daily averages of measured (x-axis) and modelled (y-axis) surface water temperatures for the validation period. The solid line indicates the regression equation, and the dashed line represents the 1:1 line.

3.3. Model validation for evaporation rates

In Figure 7, a satisfactory agreement between the daily evaporation rates estimated using the water balance method and using DYRESM can be seen. The coefficient of determination was 0.72 with a root-mean-square error of 0.38 mm day^{-1} and a mean bias error of $-0.05 \text{ mm day}^{-1}$. Likewise, Figure 8 shows a good agreement between the daily evaporation rates estimated using the eddy covariance model (Eq. 07) and DYRESM. The coefficient of determination was 0.85 with a root-mean-square error of 0.57 mm day^{-1} and a

mean bias error of $-0.20 \text{ mm day}^{-1}$. Based on these results, DYRESM was considered an appropriate model for the prediction of daily evaporation rates from Logan’s Dam.

Figure 7. Relationship between daily evaporation rates estimated using the water balance method (x-axis) and DYRESM (y-axis). The solid line indicates the regression equation, and the dashed line represents the 1:1 line. Only periods without inflows and outflows were considered to minimise errors.

Figure 8. Relationship between daily evaporation rates estimated using the eddy covariance model (x-axis) and DYRESM (y-axis). The solid line indicates the regression equation, and the dashed line represents the 1:1 line.

3.4. Modelled water temperatures

3.4.1. Water temperatures in the baseline simulations (without artificial destratification)

The modelled water temperatures of the baseline simulations (without artificial destratification) for the shallow, medium and deep lake scenarios are presented in Figure 9(a), (d) and (g), respectively. The period of simulation was 29/09/2009 to 11/04/2010, covering spring, summer and autumn months.

Figure 9. Modelled water temperatures under normal conditions (without artificial destratification) and under “weak” and “strong” artificial destratification conditions for a shallow (a—c), medium (d—f) and deep (g—i) lakes throughout the study period (29/09/2009 to 11/04/2010). In the “weak destratification” simulations, the number of ports was 1, and the air-flow rate per port was $0.001 \text{ m}^3 \text{ s}^{-1}$ (continuous operation). In the “strong destratification” simulations, the number of ports was 40 and the air-flow rate per port was $1.0 \text{ m}^3 \text{ s}^{-1}$ (continuous operation). For reference, in Australia, September, October and November are spring months; December, January and February are summer months; and March and April are autumn months.

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422 Persistent thermal stratification clearly developed in the medium and deep lake
423 cases, while the shallow lake was well mixed for almost the entire duration of the study
424 period. For the medium and deep lakes, the strongest thermal stratification levels occurred
425 between the beginning of December 2009 and the end of February 2010 (summer months).
426 This was particularly due to high air temperatures and incoming solar radiation rates
427 observed during this period. For both medium and deep lakes, the average depth of the
428 well-mixed layer was 0.8 m, reflecting a low level of mixing, and a high level of
429 stratification in these lakes. This is opposed to the average depth of the well-mixed layer in
430 the shallow lake, which was 3.3 m, showing a high level of mixing and a low level of
431 thermal stratification. For the shallow lake, some level of thermal stratification was
432 observed in the beginning of November 2009, the second week of December 2009 and in
433 the beginning of March 2010, following periods of very low wind conditions ($< 1.5 \text{ m s}^{-1}$)
434 and relatively high air temperatures ($> 26^{\circ}\text{C}$), which led to the development of a
435 temperature gradient in the metalimnion of about $4.0^{\circ}\text{C m}^{-1}$. The difference between bottom
436 and surface water temperatures in the shallow lake scenario, however, never exceeded
437 5.0°C during the time of study. For the medium lake, the strongest thermal stratifications
438 were observed on the 2nd and 20th of December 2009, 1st of February 2010 and from the
439 27th of February to the 2nd of March 2010. During these days and periods, the temperature
440 gradients in the thermocline were all above $6.0^{\circ}\text{C m}^{-1}$. The maximum gradient occurred on
441 the 2nd of March 2010 ($6.5^{\circ}\text{C m}^{-1}$). The differences in water temperature between the
442 bottom and the surface of the medium lake ranged from 2.5°C to 13.3°C , with an average of
443 8.6°C . For the deep lake case, the strongest thermal stratifications were observed on the 2nd
444 of December 2009, between the 31st of January and the 3rd of February 2010, and on the
445 26th of February 2010. During these days and periods, the temperature gradients in the

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thermocline were all above $7.0^{\circ}\text{C m}^{-1}$, with a maximum of $8.2^{\circ}\text{C m}^{-1}$ on the 1st of February 2010. Similar to the medium lake scenario, the differences in water temperature between the bottom and the surface of the deep lake ranged from 2.5°C to 13.5°C , with an average of 8.6°C .

Due to the same heat forcing conditions, the water temperatures at the surface of the three lakes were very similar, ranging from 20.6°C to 31.1°C over the 195 days of study in the shallow lake scenario (with an average of 26.6°C), from 20.2°C to 31.0°C in the medium lake scenario (average of 26.3°C) and from 20.1°C to 31.1°C in the deep lake scenario (average of 26.3°C). For the three lakes, the highest surface water temperatures ($>30^{\circ}\text{C}$) occurred in the second week of December 2009 (summer)– due to the occurrence of the highest air temperatures ($>28.6^{\circ}\text{C}$) in the study period and relatively high solar radiation (around 305 W m^{-2}) – and in the last week of January 2010 (summer) – due to the occurrence of the highest solar radiation values ($> 320\text{ W m}^{-2}$) in the study period and relatively high air temperatures (around 27°C). The average temperature of the bottom water was 25.2°C in the shallow lake, and 17.6°C in the medium and deep lakes. These figures demonstrate, again, a high level of mixing in the shallow lake when compared with the medium and deep lakes.

3.4.2. Water temperatures in the simulations with artificial destratification (continuous operation)

The modelled water temperatures of the simulations with artificial destratification for the shallow, medium and deep lake scenarios, and for a “weak” and a “strong” destratification cases, are presented in Figure 9 (b, e, h, c, f and i). In the “weak destratification” cases (Figure 9 - b, e and h), a 1-port destratification system with a per-port air-flow rate equal to $0.001\text{ m}^3\text{ s}^{-1}$, operating continuously over the 195 days of

simulation, was used. In the “strong destratification” cases (Figure 9 - c, f and i), a destratification system with 40 ports and an air-flow rate per port equal to $1.0 \text{ m}^3 \text{ s}^{-1}$, operating continuously over the 195 days of simulation, was used. Simulations with intermediate levels of artificial destratification (i.e. number of ports equal to 5, 10 and 20; and air-flow rate per port equal to $0.01 \text{ m}^3 \text{ s}^{-1}$, $0.05 \text{ m}^3 \text{ s}^{-1}$ and $0.25 \text{ m}^3 \text{ s}^{-1}$) were also performed, but have not been shown in the figures.

For the medium and deep lake cases, which developed a strong thermal stratification structure under natural conditions, the significance of the effect of artificial destratification on lake temperatures was clearly visible, even when a low air-flow rate was used. In the “weak destratification” case, however, the time to achieve a homothermous condition was longer than this time in the “strong destratification” case, in which a homothermous condition was achieved within less than one day.

Also noticeable from the graphs in Figure 9 is that, in the medium and deep lake cases, the artificial destratification system seemed to have promoted heating of the deep layers, rather than cooling of the surface layers, as was desired. While there was an effective breakdown of the thermocline (particularly in the “strong destratification” cases), which can be desirable from the point of view of water quality, the heating of the deep layers and the meaningless cooling of the surface layers are not desirable from the point of view of evaporation reduction (evaporation reduction will be discussed in more detail in the following section). The average surface water temperatures under “strong destratification” conditions were 22.0°C , 25.9°C , 28.0°C , 28.4°C , 27.6°C and 24.9°C in October, November, December, January, February and March, respectively, in the deep lake scenario, which did not differ significantly from the baseline surface water temperatures, calculated as 23.1°C , 26.6°C , 27.9°C , 28.5°C , 27.2°C and 24.5°C in these months. The “strong destratification” system, therefore, provided only slight temperature changes (-5%, -3%, 0%, 0%, 1%, 2%,

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respectively for the above months) in comparison with the baseline scenario, with higher reductions occurring in October and November (i.e. at the beginning of the operation of the destratification system, as it had been already demonstrated in a previous study – Helfer et al., 2011b).

In the medium lake scenario, the surface temperatures under “strong destratification” were 22.6°C, 26.5°C, 28.1°C, 28.6°C, 27.4°C and 24.5°C in October, November, December, January, February and March, respectively. In the baseline simulation, these temperatures were 23.1°C, 26.7°C, 27.9°C, 28.5°C, 27.2°C and 24.5°C, respectively. The changes observed were, therefore, -2%, -1%, 1%, 0%, 1%, 0% in comparison with the baseline surface water temperatures of the medium lake.

Under “weak destratification” conditions (1 port and 0.001 m³ s⁻¹ air-flow rate per port), the surface temperatures were 23.1°C, 26.6°C, 27.9°C, 28.5°C, 27.3°C and 24.6°C in the medium lake scenario, and 23.1°C, 26.5°C, 27.7°C, 28.4°C, 27.1°C and 24.5°C in the deep lake scenario. These temperatures were virtually the same as the baseline temperatures, meaning that the “weak destratification” system did not alter the surface conditions of the water in comparison with the baseline conditions.

A conclusion was drawn that the use of a “weak destratification” system in a thermally stratified reservoir (such as the medium and the deep lakes considered in this study) would not affect the surface water temperatures in comparison with that expected without the use of an artificial destratification system. Therefore, it could be inferred that evaporation rates would not be reduced with a “weak destratification” system. As shown in Figure 9 (e and h), “weak destratification” systems would mix the water at a much slower rate as compared with “strong destratification” systems, meaning that the “stock” of cold water at the bottom of the lake would take longer to be depleted with “weak destratification” systems. Although mixing would eventually be achieved with the use of

521 “weak destratification” systems, these systems would not be strong enough to lift the cold
522 water from the bottom to the surface of the reservoir, and thus promote temperature and
523 evaporation reductions.

524 Another important conclusion was that “strong destratification” systems operating
525 in thermally stratified lakes, as opposed to “weak destratification” systems, would be
526 effective in lifting the cold water from the bottom layers to the surface layers, effectively
527 reducing the surface temperatures, which would probably translate to some level of
528 evaporation reduction. This behaviour, however, would only occur at the beginning of the
529 operation of the destratification system, when the “stock” of cold water at the bottom of the
530 lake would be abundant. Within a short period, however, this stock would be depleted. This
531 postulation was apparent from Figure 9 (f and i), in which it can be seen that the
532 thermocline was disintegrated more rapidly in the “strong destratification” case than in the
533 “weak destratification” case. The rapid exhaustion of the “stock” of cold water under
534 “strong destratification” conditions would also mean that further surface water temperature
535 reductions would not be able to be achieved. These observations implied that there must
536 exist an optimum period of operation, or an operation strategy, of the destratification
537 system that will provide maximum temperature reductions and maximum evaporation
538 reductions. This supposition will be explored in sections 3.5.2 to 3.5.6 of this paper.

539 For the shallow lake, which presented a homothermous regime throughout the study
540 period, the use of artificial destratification systems did not bring any noteworthy alteration
541 to the thermal behaviour of the lake. The temperatures were the same as the baseline
542 temperatures in all destratification simulations undertaken in this study. This behaviour was
543 expected as shallow lakes usually do not develop an apparent stratification structure, and
544 thus, they do not possess a large quantity of cold water in their bottom layers.

3.5. Modelled evaporation rates

3.5.1. Baseline evaporation rates (without artificial destratification)

The modelled baseline evaporation rates from the shallow, medium and deep lake scenarios are presented in Figure 10. Due to having the same boundary conditions, the daily evaporation rates for the three scenarios were very similar. For the three lakes, the daily evaporation rates varied from 1.0 mm on the 8th of March 2010 (autumn) to 11 mm on the 19th of January 2010 (summer). There were 10 clear peaks when the daily evaporation rates were above 8.0 mm day⁻¹. These peaks in evaporation resulted from a combination of high air temperatures, wind speed, solar radiation fluxes and vapour pressure deficits. The 30-day period with the highest evaporation rates was from 19th of November 2009 to 18th of December, with a daily average of 6.2 mm day⁻¹. The 7-day period with the highest evaporation rates was from the 13th to the 19th of January 2010, with an average of 7.1 mm day⁻¹. Total evaporation for the 195 days was 906 mm in the shallow lake scenario, and 894 mm in both the medium and deep lake scenarios. The slightly higher total evaporation in the shallow lake scenario was a result of the surface temperature in the shallow lake being on average slightly warmer than in the deeper lakes.

Figure 10. Modelled daily evaporation rates from the shallow, medium and deep lakes throughout the study period (29/09/2009 to 11/04/2010). Baseline values (without artificial destratification).

3.5.2. Evaporation rates in the simulations with artificial destratification (continuous operation)

Figure 11 summarises the 195-day accumulated evaporation for different levels of artificial destratification (i.e. combination of number of ports and air-flow rate per port) for the medium (a) and deep (b) lake scenarios. Since the use of artificial destratification did

not induce temperature and evaporation changes in the shallow lake scenario, the results for this scenario have been omitted from this point forward. A preliminary conclusion was drawn in the previous section that the use of artificial destratification systems for the purpose of evaporation reduction from lakes that experience homothermous regimes (which is a typical occurrence in shallow lakes) would not be worthwhile.

Figure 11. Total evaporation as a function of the number of destratification ports and air-flow rate per port for the medium and deep lake scenarios. In Figure (c), the blue lines represent the total evaporation as a function of the number of ports, with a fixed air-flow rate per port equal to $0.001 \text{ m}^3 \text{ s}^{-1}$ (the lowest air-flow rate per port simulated in this study). The red lines represent the total evaporation as a function of the number of ports, with a fixed air-flow rate per port equal to $1.0 \text{ m}^3 \text{ s}^{-1}$ (the highest air-flow rate per port simulated in this study). The total evaporation as a function of the number of ports for air-flow rates per port between $0.001 \text{ m}^3 \text{ s}^{-1}$ and $1.0 \text{ m}^3 \text{ s}^{-1}$ would fall between the curves shown in the graph, although omitted in the figure. The baseline evaporation (without artificial destratification) for both lakes was 894 mm and is represented in the graph when the number of ports = 0.

As discussed in the previous section, the accumulated evaporation in the baseline simulations (without artificial destratification) was 894 mm for both the medium and deep lakes. Under artificial destratification conditions, for both lakes, the reduction in evaporation increased with the increase in number of ports and air-flow rate per port. The deep lake scenario presented higher evaporation reductions than the medium lake scenario in all artificial destratification conditions simulated in this study. The total evaporation from the medium lake ranged from 888 mm to 891 mm under the use of artificial destratification systems. The lowest value of the range (888 mm) was achieved in the simulation where the highest number of ports (40 ports) and the highest air-flow rate per

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port ($1.0 \text{ m}^3 \text{ s}^{-1}$) were assumed. In turn, the highest value of the range (891 mm) was observed in the simulation with the lowest number of ports (1 port) and the lowest air-flow rate per port ($0.001 \text{ m}^3 \text{ s}^{-1}$). These evaporation values represent water savings in the order of 0.5% and 0.2%, respectively, which is likely not to justify the use of continuously operating artificial destratification systems for the sole purpose of evaporation reduction in reservoirs of this size.

 In the deep lake simulations, the accumulated evaporation varied from 868 mm to 878 mm with the use of artificial destratification systems, representing savings from 2.9% to 1.8%. It is important to note, however, that the highest reduction (2.9%), which could be interpreted as a meaningful saving in regions where water is scarce and or/expensive, would only be achieved with the use of a very high flow rate per port ($1.0 \text{ m}^3 \text{ s}^{-1}$) combined with a large number of ports (40). This condition would require so much energy that implementation of the system would be unlikely justifiable. It was, therefore, concluded that the use of artificial destratification systems in continuous operation would be futile because this operating strategy would only achieve slight evaporation reductions that are unlikely to justify the investment and operational costs of the destratification system.

 Time series analyses of the lake temperatures and daily evaporation rates under continuously operating destratification conditions showed that the reductions in surface water temperatures and evaporation rates were more significant immediately after the breakdown of the thermocline. Under “strong destratification” conditions, for example, the breakdown of the thermocline occurred within a few hours from the beginning of operation of the destratification system, and the evaporation reductions started to occur from this time forward, sustaining for about 30 days. After 30 days, there was a period in which the surface temperatures and evaporation rates became practically the same as the baseline temperatures and evaporation rates, followed by a period (end of the period of simulation)

during which the surface temperatures and evaporation rates under destratification conditions were higher than the baseline values. Under “weak destratification” conditions, evaporation reductions began to be noted about 30 days after the beginning of the operation of the systems. This delay was because the thermocline was dismantled more slowly under these less intense destratification systems. The evaporation time series for these simulations are presented in Figure 12.

Figure 12. Modelled daily evaporation rates from the medium (a) and deep (b) lakes under continuous (uninterrupted) “weak destratification” conditions (1 port and per-port air-flow rate = $0.001 \text{ m}^3 \text{ s}^{-1}$) – green lines; “strong destratification” condition (40 ports and per-port air-flow rate = $1.0 \text{ m}^3 \text{ s}^{-1}$) – red lines; and under baseline conditions (without destratification) – blue lines.

The above observations suggested the hypothesis that destratification systems could achieve more significant evaporation reductions if they were set to operate over a given period of time, and then switched off for the rest of the period to avoid the increased evaporation rates at the end of their operation. This hypothesis was tested by undertaking a number of simulations that considered a number of different operating strategies, and the results are presented in the next sections. Since the medium lake scenario presented only minimal differences in relation to the baseline evaporation rates, attention in the next sections is devoted only to the deep lake scenario.

3.5.3. Evaporation under the use of a destratification system, operating continuously over a 30-day period

Figure 13 shows the modelled time series of daily evaporation rates with the use of a destratification system set to operate for six different 30-day periods (October, November,

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December, January, February and March). The principle behind this strategy was that destratification would cause reductions in evaporation when in operation, avoiding the increase in evaporation at the end of the simulation period, as observed in the simulations with continuous operation. The destratification system design chosen for these simulations was the one with 40 ports and air-flow rate per port equal to $0.001 \text{ m}^3 \text{ s}^{-1}$. This design was selected based on the curves shown in Figure 11. This graph suggested that a destratification design with a large number of ports and a low air-flow rate per port would bring similar savings to a design with one port only and a high air-flow rate per port. In order to achieve an effective mixing, the use of a low number of ports would require high air-flow rates per port, a condition that would also involve a significant consumption of energy. Conversely, the use of a large number of ports, uniformly distributed in the bottom of the reservoir, would still provide effective mixing even with a very low air-flow rate, and incur much less energy consumption.

Figure 13. Modelled daily evaporation rates from the deep lake with the use of a destratification system in continuous operation for 30 days in October (a), November (b), December (c), January (d), February (e) and March (f) – red lines. The baseline evaporation time series are represented by the blue lines.

Figure 13 clearly shows that evaporation reductions took place in times when artificial destratification systems were in operation. However, these reductions were only sustained for the duration of the operation of the destratification systems, reaching the same rates as the baseline rates after they were switched off. The reductions varied from 1.5% (operation in October) to 2.3% (operation in January). The cooling of the surface by the destratification system had a better effect when in operation in January due to the higher atmospheric evaporative demand in this month. The lowest reductions in evaporation were

found when the system operated in October and in March. This is because the evaporative demand in these months was not as high, and the displacement of cold bottom water to the surface did not generate the desired effect. Despite the reductions noted in these simulations with monthly operation of the destratification systems, a conclusion was drawn that these reductions would not justify investment and operation costs.

3.5.4. Evaporation under the use of a destratification system operating in monthly and weekly cycles

Further simulations were performed with operation strategies based on weekly and monthly cycles. In the monthly cycles, the destratification system was in continuous operation for periods of 30 days, separated by interruptions of 30 days between periods of operation. In the weekly cycles, the system was in operation for periods of 7 days, separated by interruptions of 7 days. The destratification system design adopted in the simulations was the same as in the previous operation strategy (40 ports and air-flow rate per port equalling $0.001 \text{ m}^3 \text{ s}^{-1}$). The principle behind the operation in cycles was that the system would provide evaporation reductions when in operation, and thermal stratification would develop in the lake during the breaks. In this way, at the beginning of each operation period, there would be a good source of cold water to bring about surface temperature and evaporation reductions.

The operation in cycles yielded better results than the previous operation strategy; however, the reductions would still be unlikely to justify investment and operational costs of the destratification system. The reductions were 2.4% for the weekly cycles, and 2.6% for the monthly cycle. The time series of evaporation rates for these simulations are presented in Figure 14.

Figure 14. Modelled daily evaporation rates from the deep lake with the use of a destratification system operating in monthly (a) and weekly (b) cycles – red lines. The baseline evaporation time series are represented by the blue lines.

3.5.5. Evaporation under the use of a destratification system operating in pulses

The principle behind this operation strategy is that a strong injection of air, with high intensity and short duration, would break down the thermocline and lift the cold water from the bottom to the surface in a short period, reducing evaporation rates. Then, the system would be interrupted for a period of time long enough to allow the re-establishment of a stratification structure with accumulation of cold water at the bottom. After this period, a pulse of destratification would be provided again. Two different strategic options were tested: the first had a high frequency (the system would be turned on every fortnight) and low intensity ($0.01 \text{ m}^3 \text{ s}^{-1}$) pulse; the other had a pulse with low frequency (every month) and high intensity ($0.05 \text{ m}^3 \text{ s}^{-1}$). The number of ports was left constant at 40 ports per diffuser, and the duration of the pulse was set as 1 day for both cases. The results are shown in Figure 15.

Figure 15. Modelled daily evaporation rates from the deep lake with the use of a destratification system operating in pulses: (a) higher frequency (fortnightly) and lower intensity ($0.01 \text{ m}^3 \text{ s}^{-1}$) pulse; (b) lower frequency (monthly) and higher intensity ($0.05 \text{ m}^3 \text{ s}^{-1}$) pulse – red lines. The baseline evaporation time series are represented by the blue lines.

It was observed that the operation of the destratification system in pulses caused reduction in evaporation rates, particularly immediately after the operation and in months of high evaporative demands. In general, the reductions were sustained from November

727 until mid-February in the scenario with fortnightly pulses, but the total reduction was only
 728 2.3% in comparison with the baseline scenario. In the scenario with monthly pulses, the
 729 reductions were sustained for about two weeks after the pulse, reaching the same
 730 evaporation rates as the baseline rates after this time. The total reduction was also 2.3%.
 731 Neither way is likely to justify the adoption of these operation strategies.

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733 *3.5.6. Evaporation under the use of a destratification system operating in November and* 734 *January, and in December and February*

735 A final operation strategy was tested, with the destratification system in operation
 736 only in months when the evaporative demands were high. The first option was with the
 737 destratification system operating in November and January. The second option was with the
 738 destratification system operating in December and February. For both options, the number
 739 of ports was 40, and the air-flow rate per port was $0.001 \text{ m}^3 \text{ s}^{-1}$. The results are presented in
 740 Figure 16.

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742 **Figure 16. Modelled daily evaporation rates from the deep lake with the use of a**
 743 **destratification system operating in November and January (a), and in December and**
 744 **February (b) – red lines. The baseline evaporation time series are represented by the**
 745 **blue lines.**

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747 Reductions in evaporation occurred in both cases, being 2.2% for the first case
 748 (destratification system operated in November and January), and 2.3% for the second case
 749 (destratification system operated in December and February). The reductions were more
 750 significant in the first month of operation (i.e. in November for the first case, and in
 751 December for the second case). The reductions were not significant in the second month of
 752 operation (i.e. in January for the first case, and in February for the second case). There were

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753 slight increases in evaporation after the second month of operation due to the increase in
754 water temperatures brought about by the mixing device. Since only minor reductions were
755 reached with these operation strategies, it was concluded that it would not be worthwhile to
756 use these strategies for evaporation reduction.

757 Table 2 summarises the results of this study, showing the overall evaporation
758 reductions achieved from different destratification operating strategies adopted in the deep-
759 lake scenario.

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761 **Table 2. Summary of the overall evaporation reductions achieved with the use of**
762 **various destratification operating strategies. Note: Only the most promising strategies**
763 **are displayed in the table, and the results are for the deep lake scenario only.**
764

765 **4. Conclusions**

766 The effectiveness of artificial destratification by air-bubble plumes in reducing
767 evaporation from reservoirs was investigated in this study. The following conclusions were
768 drawn:

- 769 • Artificial destratification systems will reduce evaporation rates if employed in
770 reservoirs that experience thermal stratification and have an abundant ‘stock’ of cold
771 water at the bottom. The reduction in evaporation rates can be higher in deeper
772 reservoirs, because these reservoirs can supply larger volumes of colder water for
773 mixing with surface waters;
- 774 • The reductions in evaporation rates will increase with the increase in number of ports
775 and with the increase in air-flow rate per port of the destratification system. Although
776 this hypothesis requires testing, increasing the number of ports and keeping a low air-

777 flow rate per port is probably more advantageous than reducing the number of ports
778 and increasing the air-flow rate per port, due to the first option requiring less energy;
779 • There was only a small variation in evaporation reduction depending on the operating
780 strategy of the artificial destratification system. The operating strategy that brought
781 about higher evaporation reductions (2.9%) was the continuous operation system with
782 40 ports and air flow rate per port equal to $1.0 \text{ m}^3 \text{ s}^{-1}$;
783 • While seeming small, water savings from destratification systems may be significant
784 in countries where water is scarce and the production of fresh water is highly
785 expensive. A study to investigate energy requirements and the economic feasibility of
786 the most promising destratification designs and operation strategies (as shown in
787 Table 2) is therefore a recommendation for further research.

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795 data and measurements.
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Figure 1. Aerial view of the agricultural reservoir investigated in the current study (from Google Earth) and its location in Australia. Location of centre of reservoir: 27°34'26''S, 152°20'27''E. Surface area: 17 hectares (170,000 m²).

Figure 2. Average daily shortwave solar radiation, air temperature, wind speed, vapour pressure deficit and total daily rainfall at Logan's Dam throughout the study period. For reference, in Australia, the spring months are September, October and November; summer months are December, January and February; autumn months are March, April and May; and winter months are June, July and August.

Figure 3. Isotherms for Logan’s Dam during the calibration period (29/09/2009 to 06/01/2010). This period covers the spring months of October and November, and the summer month of December and part of January. a) Measured data. b) Modelled data using DYRESM.

Figure 4. Relationship between daily averages of measured (x-axis) and modelled (y-axis) surface water temperatures for the calibration period. The solid line indicates the regression equation, and the dashed line represents the 1:1 line.

Figure 5. Isotherms for Logan's Dam during the validation period (07/01/2010 to 11/04/2010). This period covers the summer months of January and February, and the autumn month of March and part of April. a) Measured data. b) Modelled data using DYRESM.

Figure 6. Relationship between daily averages of measured (x-axis) and modelled (y-axis) surface water temperatures for the validation period. The solid line indicates the regression equation, and the dashed line represents the 1:1 line.

Figure 7. Relationship between daily evaporation rates estimated using the water balance method (x -axis) and DYRESM (y -axis). The solid line indicates the regression equation, and the dashed line represents the 1:1 line. Only periods without inflows and outflows were considered to minimise errors.

Figure 8. Relationship between daily evaporation rates estimated using the eddy covariance model (x -axis) and DYRESM (y -axis). The solid line indicates the regression equation, and the dashed line represents the 1:1 line.

Figure 9. Modelled water temperatures under normal conditions (without artificial destratification) and under “weak” and “strong” artificial destratification conditions for a shallow (a—c), medium (d—f) and deep (g—i) lakes throughout the study period (29/09/2009 to 11/04/2010). In the “weak destratification” simulations, the number of ports was 1, and the air-flow rate per port was $0.001 \text{ m}^3 \text{ s}^{-1}$ (continuous operation). In the “strong destratification” simulations, the number of ports was 40 and the air-flow rate per port was $1.0 \text{ m}^3 \text{ s}^{-1}$ (continuous operation). For reference, in Australia, September, October and November are spring months; December, January and February are summer months; and March and April are autumn months.

Figure 10. Modelled daily evaporation rates from the shallow, medium and deep lakes throughout the study period (29/09/2009 to 11/04/2010). Baseline values (without artificial destratification).

Figure 11. Total evaporation as a function of the number of destratification ports and air-flow rate per port for the medium and deep lake scenarios. In Figure (c), the blue lines represent the total evaporation as a function of the number of ports, with a fixed air-flow rate per port equal to $0.001 \text{ m}^3 \text{s}^{-1}$ (the lowest air-flow rate per port simulated in this study). The red lines represent the total evaporation as a function of the number of ports, with a fixed air-flow rate per port equal to $1.0 \text{ m}^3 \text{s}^{-1}$ (the highest air-flow rate per port simulated in this study). The total evaporation as a function of the number of ports for air-flow rates per port between $0.001 \text{ m}^3 \text{s}^{-1}$ and $1.0 \text{ m}^3 \text{s}^{-1}$ would fall between the curves shown in the graph, although omitted in the figure. The baseline evaporation (without artificial destratification) for both lakes was 894 mm and is represented in the graph when the number of ports = 0.

Figure 12. Modelled daily evaporation rates from the medium (a) and deep (b) lakes under continuous (uninterrupted) “weak destratification” conditions (1 port and per-port air-flow rate = 0.001 m³ s⁻¹) – green lines; “strong destratification” condition (40 ports and per-port air-flow rate = 1.0 m³ s⁻¹) – red lines; and under baseline conditions (without destratification) – blue lines.

Figure 13. Modelled daily evaporation rates from the deep lake with the use of a destratification system in continuous operation for 30 days in October (a), November (b), December (c), January (d), February (e) and March (f) – red lines. The baseline evaporation time series are represented by the blue lines.

Figure 14. Modelled daily evaporation rates from the deep lake with the use of a destratification system operating in monthly (a) and weekly (b) cycles – red lines. The baseline evaporation time series are represented by the blue lines.

Figure 15. Modelled daily evaporation rates from the deep lake with the use of a destratification system operating in pulses: (a) higher frequency (fortnightly) and lower intensity (0.01 m³ s⁻¹) pulse; (b) lower frequency (monthly) and higher intensity (0.05 m³ s⁻¹) pulse – red lines. The baseline evaporation time series are represented by the blue lines.

Figure 16. Modelled daily evaporation rates from the deep lake with the use of a destratification system operating in November and January (a), and in December and February (b) – red lines. The baseline evaporation time series are represented by the blue lines.

Table 1. Summary of the simulations with the artificial destratification system operating continuously over the period of study.

Simulation name ¹	SHAL_N_AFR	DEEP_N_AFR	MEDI_N_AFR
Initial water depth (m)	6.5	11.5	16.5
Initial water temperature	17.8°C throughout column	17.8°C throughout column	17.8°C throughout column
Number of ports	1, 5, 10, 20, 40	1, 5, 10, 20, 40	1, 5, 10, 20, 40
Air-flow rate per port (m ³ s ⁻¹)	0 (baseline), 0.001, 0.01, 0.05, 0.25, 1.0	0 (baseline), 0.001, 0.01, 0.05, 0.25, 1.0	0 (baseline), 0.001, 0.01, 0.05, 0.25, 1.0
Operation strategy of the destratification system	Continuous operation for over the period of simulation (195 days)	Continuous operation for over the period of simulation (195 days)	Continuous operation for over the period of simulation (195 days)

¹ In the simulation name, *N* refers to the number of ports and *AFR* to the air-flow rate per port. For example, the simulation SHAL_10_005 refers to the shallow lake scenario, with a 10-port destratification system and air-flow rate per port equal to 0.05 m³ s⁻¹. The baseline simulations (without the use of destratification) are represented by the simulations with air-flow rate = 0.

Table 2. Summary of the overall evaporation reductions achieved with the use of various destratification operating strategies. Note: Only the most promising strategies are displayed in the table, and the results are for the deep lake scenario only.

Operation strategy	Overall evaporation reduction (deep lake case)	Section in which operation strategy is discussed
195-day continuous operation, 1 port, 0.001 m ³ s ⁻¹ per port	2.2%	3.5.2
195-day continuous operation, 1 port, 1.0 m ³ s ⁻¹ per port	2.5%	3.5.2
195-day continuous operation, 40 ports, 0.001 m ³ s ⁻¹ per port	2.7%	3.5.2
195-day continuous operation, 40 ports, 1.0 m ³ s ⁻¹ per port	2.9%	3.5.2
30-day continuous operation in January (summer), 40 ports, 0.001 m ³ s ⁻¹ per port	2.3%	3.5.3
30-day continuous operations followed by 30 days interruptions, 40 ports, 0.001 m ³ s ⁻¹ per port	2.6%	3.5.4
7-day continuous operations followed by 7-day interruptions, 40 ports, 0.001 m ³ s ⁻¹ per port	2.4%	3.5.4
Fortnightly destratification pulses of 1-day duration, 40 ports, 0.01 m ³ s ⁻¹ per port	2.3%	3.5.5
Monthly destratification pulses of 1-day duration, 40 ports, 0.05 m ³ s ⁻¹ per port	2.3%	3.5.5
Continuous operation in November and January, 40 ports, 0.001 m ³ s ⁻¹ per port	2.2%	3.5.6
Continuous operation in December and February, 40 ports, 0.001 m ³ s ⁻¹ per port	2.3%	3.5.6