

The Impact of Artificial Destratification on Reservoir Evaporation

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Description: WEARS mixer system at Googong Reservoir
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FOREWORD

Water is fundamental to our quality of life, to economic growth and to the environment. With its booming economy and growing population, Australia's South East Queensland (SEQ) region faces increasing pressure on its water resources. These pressures are compounded by the impact of climate variability and accelerating climate change.

The Urban Water Security Research Alliance, through targeted, multidisciplinary research initiatives, has been formed to address the region's emerging urban water issues.

As the largest regionally focused urban water research program in Australia, the Alliance is focused on water security and recycling, but will align research where appropriate with other water research programs such as those of other SEQ water agencies, CSIRO's Water for a Healthy Country National Research Flagship, Water Quality Research Australia, eWater CRC and the Water Services Association of Australia (WSAA).

The Alliance is a partnership between the Queensland Government, CSIRO's Water for a Healthy Country National Research Flagship, The University of Queensland and Griffith University. It brings new research capacity to SEQ, tailored to tackling existing and anticipated future risks, assumptions and uncertainties facing water supply strategy. It is a \$50 million partnership over five years.

Alliance research is examining fundamental issues necessary to deliver the region's water needs, including:

- ensuring the reliability and safety of recycled water systems.
- advising on infrastructure and technology for the recycling of wastewater and stormwater.
- building scientific knowledge into the management of health and safety risks in the water supply system.
- increasing community confidence in the future of water supply.

This report is part of a series summarising the output from the Urban Water Security Research Alliance. All reports and additional information about the Alliance can be found at <http://www.urbanwateralliance.org.au/about.html>.



Chris Davis

Chair, Urban Water Security Research Alliance

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EXECUTIVE SUMMARY

Artificial destratification of reservoirs has been proposed periodically as a management strategy with potential to reduce evaporation. Reduction in evaporation relies on an underpinning assumption that artificial destratification will reduce the surface layer temperature sufficiently to decrease the saturated vapour pressure of the air just above the water. This in turn reduces the driving water vapour concentration gradient responsible for the evaporation.

The principle methods used to destratify reservoirs in Australia today are bubble plumes and draft-tube mixers. Bubble plumes lift deep water to the surface, whereas draft-tube mixers pump surface layer water downwards. Both methods can be expected to produce broadly similar results in terms of changes in thermal stratification over time, although they differ in detail near the upper and lower boundaries of the water column.

Two different numerical models were used to explore the potential impact of artificial destratification on evaporation rates for both theoretical and real-world systems using one year of high temporal resolution meteorological data. A one-dimensional reservoir model (DYRESM) was used to model evaporation from an idealised water column with 1 km² surface area and depths of 5, 10, 20 and 40 metres to quantify the theoretical scope for evaporation reduction. The 3-D hydrodynamic model, ELCOM, was used to model the impact of an existing surface impeller-based reservoir circulation system (WEARS) deployed at Googong Dam, assuming either continuous operation of the mixer system (the actual operating practice) or no operation of the mixer system.

Compared to the natural stratified case, the 1D model predicted <2 percent reduction in annual evaporation for water columns ≤20 metres deep undergoing artificial destratification. For the 40 metre deep water column, artificial destratification produced a 9 percent reduction in annual evaporation during the first year of operation but yielded no appreciable difference in annual evaporation between artificially mixed (1.65 metres annual evaporation) and naturally stratified (1.63 metres annual evaporation) conditions during following years.

The one-off reduction in evaporation during the first year was due to the lower initial water column heat content under natural stratified conditions. After the first year of destratification, the temperature of the fully-mixed water column in early winter was increased by 4.3 °C (from 8.4 to 12.7 °C) and this was sufficient to eliminate any reduction in annual evaporation during the second year of destratification and beyond.

Simulation using the 3-D hydrodynamic model of the state-of-the-art large scale WEARS surface draft-tube mixer system currently deployed at Googong Reservoir showed no impact of the operation of the system on annual evaporation. Comparisons between model-predicted thermal stratification and high resolution field observations were satisfactory and lend confidence to the use of this tool to predict real-world performance of artificial destratification using such systems.

It is theoretically possible for destratification to produce a continuing evaporation reduction in relatively deep reservoirs (say > 30 metres average depth) *provided* reservoir inflow and outflow volumes and temperatures are manipulated in such a way as to reduce the carry-over heat storage at winter turnover compared to equilibrium conditions. Whether or not this can be achieved in practice is reservoir-specific and depends on the timing of water supply (inflows) and demand (outflows) as well as local climatic conditions.

It is especially important to bear in mind that there is a big difference between theoretical performance (instantaneous complete mixing) and real-world performance of artificial destratification. As reservoirs increase in scale they become much more difficult and expensive to destratify.

1. INTRODUCTION

This report has been prepared for the Urban Water Security Research Alliance for the purpose of assessing the potential for water column destratification systems to reduce evaporation from water storages in South East Queensland (SEQ). This report is one of a group, each assessing the applicability of different evaporation mitigation techniques to SEQ water supply systems.

2. WHAT IS ARTIFICIAL DESTRATIFICATION?

Artificial destratification refers to the use of mechanical energy to enhance the vertical transport of heat in a reservoir in order to reduce the strength of the vertical temperature gradient in the water column. The temperature gradient is the natural product of solar heating: most of the sun's energy is absorbed close to the water surface, causing it to warm faster than the water below. The heating process is strongest during spring and summer, and the resultant stratification increases the water column's resistance to vertical mixing (e.g. Ashby and Kennedy 1993; Lemckert and Imberger, 1993; Lawson and Anderson, 2007).

Traditionally, artificial destratification has been used mainly in attempts to modify chemical water quality and to control phytoplankton growth (McAuliffe and Rosich, 1989; Sherman et al., 2000), although it is periodically considered as a method to reduce evaporation (Hughes et al., 1975; van Dijk and van Vuuren, 2009). In Australia, the goal of improved chemical water quality is more often achieved than controlling phytoplankton growth, especially when the noxious phytoplankton are buoyant cyanobacteria (McAuliffe and Rosich, 1989; Littlejohn, 2004). In the first case, the most common requirement is to increase dissolved oxygen levels at depth within the water column in order to reduce concentrations of undesirable constituents, such as reduced forms of iron and manganese, and to reduce internal nutrient loading from the bottom sediments.

Reservoir destratification systems are mechanical devices designed to reduce water column stratification and increase the vertical transfer of dissolved oxygen (Fast 1968; Klapper, 2003). Destratification systems are generally designed to lift cold bottom water (hypolimnion) through the thermocline and into the surface waters (epilimnion) where it mixes with the warmer surface waters before falling back down to a level of neutral buoyancy (Section 2.1). This produces a large-scale circulation in the reservoir that effectively results in a net downwards velocity that carries heat and dissolved oxygen from the surface towards the sediments. The magnitude of the downwards heat flux is essentially an engineering design decision. A more isothermal water column can be produced more quickly by increasing the number of plumes or mixers. This requires higher initial capital investment and probably higher operating costs. However, a larger destratification system may not have to be operated for as long as a smaller system to produce a given level of destratification. In this case, total annual operating costs would not necessarily scale in proportion to the capacity of the system.

The most common approaches to artificially destratify a reservoir are to use bubble plumes, draft-tube mixers, or unconfined mixers (Figure 1)). All three approaches work in a qualitatively similar way to each other, described in detail below, but differ with regard to their characteristics near the upper and lower boundaries of the water column. Bubble plumes and draft-tube mixers are always oriented vertically. Unconfined mixers may be oriented vertically (just like a draft-tube mixer without the draft tube) or they may be oriented obliquely so that the jet they produce projects diagonally through the water column. This latter configuration is sometimes employed when the mixers are mounted onto a dam wall, e.g. Myponga reservoir (Steffenson, pers. comm.).



Figure 1. Destratification systems. Clockwise from top left: 10 bubble plumes at Chaffey Dam, NSW; WEARS draft-tube mixer awaiting deployment (photo courtesy WEARS); WEARS mixer deployed at Myponga Reservoir, SA.

2.1. Bubble Plumes

A typical bubble plume system consists of a land-based compressor which delivers air to the bottom of the reservoir through a pipe. Bubble plumes are produced as air is released through a diffuser which may simply be a pattern of holes drilled into the pipe that somewhat resembles a shower head, or it may be a more elaborately designed structure. Bubble plume systems have been deployed as 'curtains' using linear plumes (regular, relatively closely spaced individual plumes) and as series of discrete plumes designed to not interact with each other so as to maximise the amount of ambient water entrained into each plume.

The dynamics of a single bubble plume are well understood and can be accurately modelled using reservoir dynamics models (Schladow, 1992). Multiple bubble plume systems are typically assumed to consist of non-interacting individual plumes, which allows their simulation using single plume theory. As a bubble plume rises, it entrains ambient water from all along the water column and lifts this water towards the surface (Figure 2). Eventually, the water being lifted by the bubbles will detrain from the bubbles and form an intrusion that propagates away from the plume outwards into the water column. It is possible for detrainment to occur more than once as the bubbles rise to the surface but it is most common to design bubble plume systems so that detrainment occurs only when the plume reaches the surface.

Maximum efficiency¹ of destratification by bubble plumes is achieved when individual bubble plumes do not interact with one another. Also, the efficiency of destratification decreases as the water column stratification weakens, e.g. destratification of a strongly stratified water column ($T_{\text{top}} - T_{\text{bottom}} = \Delta T \sim 10\text{-}12\text{ }^{\circ}\text{C}$) may commence at, say, 9 % but reduce to < 1 % when $\Delta T \sim 0.5 - 1\text{ }^{\circ}\text{C}$.

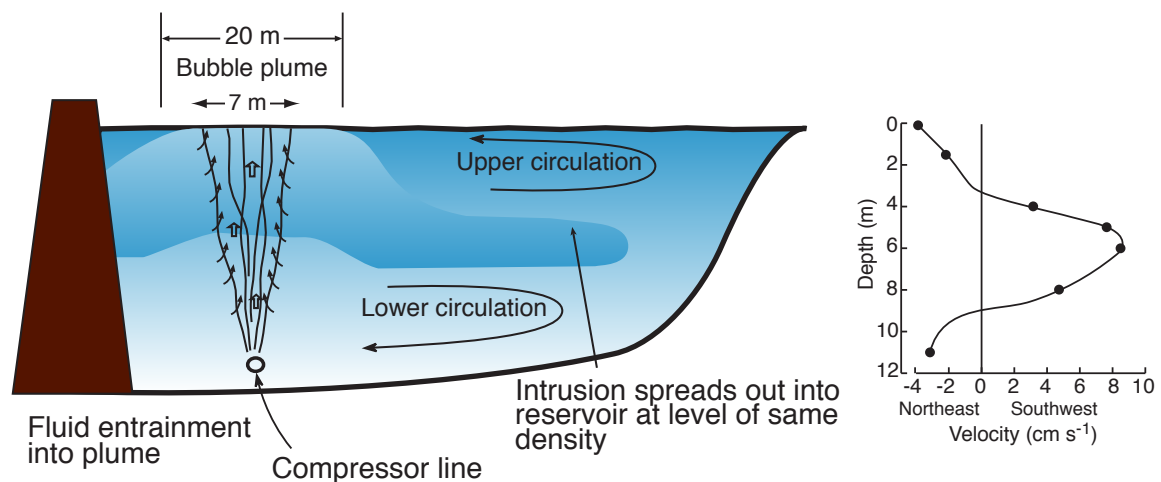


Figure 2. Circulation pattern resulting from bubble-plume destratification. (from Sherman et al. 2000)

¹The efficiency of artificial destratification is the ratio of the change in potential energy (PE) of the water column to the amount of energy expended to produce the change in PE. PE is computed as:

$$\int_0^H \rho(z)A(z)gz dz$$

where H is the water column depth, ρ is density and A is the area at height z above the bottom. PE is greatest when the water column is completely mixed.

The intrusive flow sets up upper and lower circulation gyres which produce a net downwards flux of heat in the water column. The downwards heat flux reduces the temperature difference between the top and bottom of the water column thereby reducing the strength of the stratification. Only the surface layer water directly entrained into the bubble plume is transported downwards; there is no direct supplemental downwards transport of heat away from the bubble plumes unless destratification has facilitated greater deepening of the surface mixed layer (SML) by reducing the resistance of the water column to SML deepening due to surface cooling and wind mixing. Experience has shown that that in most cases in Australia, destratification has not produced a consistently deeper surface mixed layer although it may increase the susceptibility to deepening from unusually cold and/or windy weather (Sherman et al., 2000; Sherman, 2008; Littlejohn, 2004).

As an example, the bubble plume system at Chaffey Dam, NSW, (shown in Figure 1) was designed as ten non-interacting plumes, each with an air-flow rate of 10 L s^{-1} . The water column was approximately 28 m deep and each plume had a diameter of approximately 7 m at the surface, where bubbles were clearly visible. The radial outwards flow at the surface plunged down to the level of neutral buoyancy roughly 10 m from the centre of each plume. The intrusion propagated away from the plumes at a depth of 4-8 m and a maximum velocity of 0.08 m s^{-1} (Figure 2). This is nearly 7 km per day, but bear in mind that the velocity decreases with distance from the plumes. Fine structure temperature profiles suggested high levels of turbulence within the plume region. Away from the 20 m region centred on the bubble plumes there was little, if any, increase in vertical turbulent transport in the stratified water column - the intrusion propagates as a relatively quiescent flow.

Response of the reservoir's thermal stratification to the commencement of bubble plume destratification is rapid (Figure 3). At Chaffey Dam, destratification commenced in early October and within a fortnight a $5 \text{ }^\circ\text{C}$ temperature difference was reduced to about $2 \text{ }^\circ\text{C}$. Continued operation during spring produced an overall warming of the water column but no further reduction in the strength of the stratification. Continued operation of the system into the summer could be expected to eventually decrease the top-to-bottom temperature difference because there is an upper limit to how warm the surface mixed layer can become due to temperature feedbacks through sensible, latent and long-wave emission heat fluxes from the water surface as well as seasonal changes in meteorological parameters.

The consistent temperature gradient during destratification shown in Figure 3 shows that the circulation generated by the destratification system transported heat downwards at approximately the same rate as air-water heat fluxes introduced heat into the water column. Had the vertical transport been greater than the incoming heat flux then the temperature difference would diminish over time.

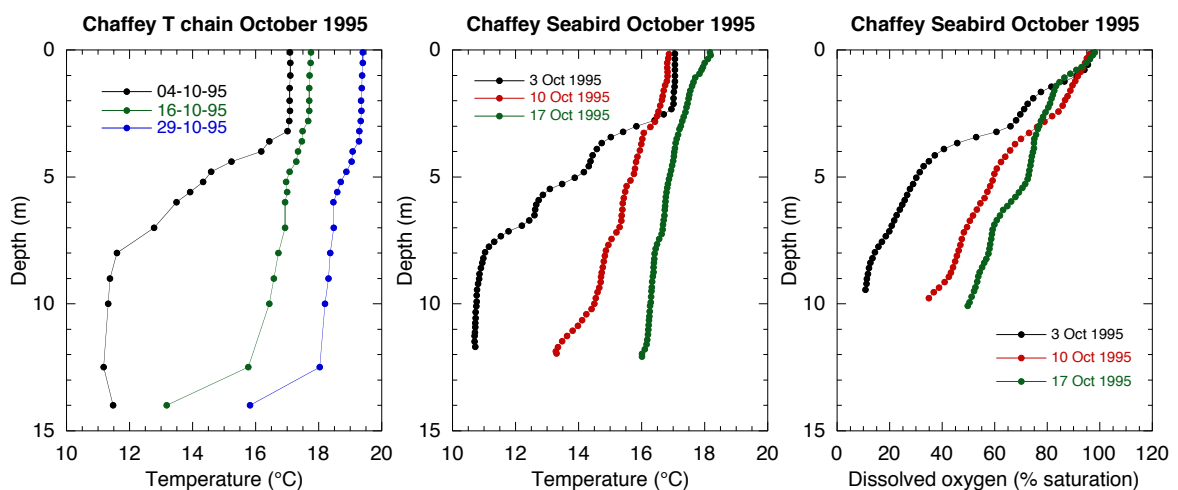


Figure 3. Response of thermal stratification to bubble plume destratification in Chaffey Dam (data from Sherman et al., (2001)). Left, thermistor chain data; centre, Seabird SBE19 temperature profile; right, Seabird SBE19 dissolved oxygen profile.

2.2. Surface Pumps and Draft Tube Mixers (DTMs)

Surface pumps and draft tube mixers reduce stratification by producing a similar circulation pattern to that produced by bubble plumes, with the following difference. A jet and/or plume is produced that entrains water from the adjacent water column and produces an intrusive flow and large scale circulation similar to that produced by bubble plumes. Instead of the bottom-up approach of releasing a stream of buoyant gas at the bottom that carries cold water towards the surface, impeller based systems physically pump surface layer water downwards either as an unconfined jet (surface pump) beginning at the level of the impeller or as a jet emanating from the bottom of a draft tube (Figure 4). Impeller systems can also be used as a direct replacement for bubble plume systems by locating the pump at the bottom of the water column and pumping the water vertically upwards. Stevens and Imberger (1993) conducted laboratory experiments on an upwards-facing pump-type system and observed efficiencies of 6-12 % when destratifying a two-layer fluid.

When water is pumped through an impeller it will propagate as a jet over a distance Z_p (Figure 4), at which point the momentum of the jet is balanced by a resisting pressure force arising from the density change between the source water and the water nominally at depth Z_p . It can be shown that for a two-layer stratification this depth varies as:

$$Z_p = \frac{1}{2} \frac{\rho u^2}{g \Delta \rho}$$

where ρ is the initial density of the jet with velocity, u , and $\Delta \rho$ is the density difference between the layers. As the temperature difference increases, $\Delta \rho$ increases and the jet is not able to penetrate as far through the water column.

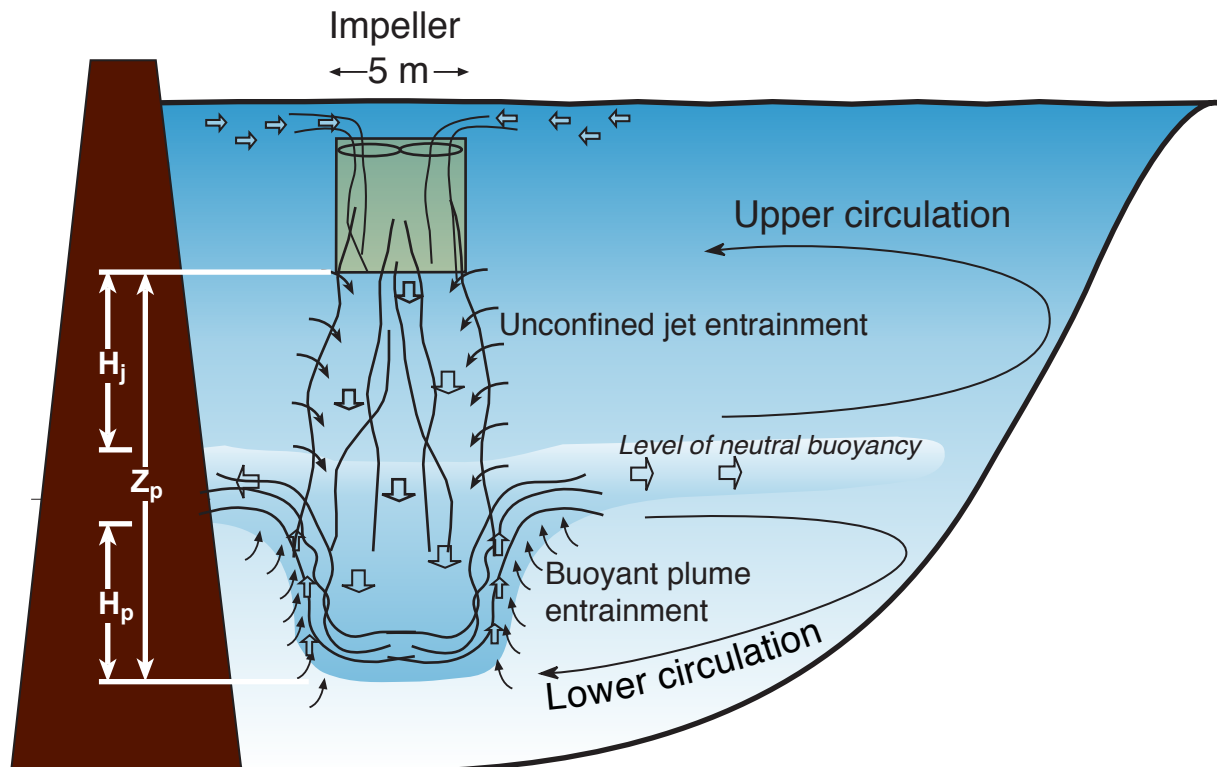


Figure 4. Circulation pattern resulting from surface pump destratification. An impeller is located near the water surface and pumps water downwards. A draft tube mixer is similar to a surface pump with the addition of a draft tube (shown in gray) to eliminate entrainment of ambient fluid from the water column adjacent to the draft tube.

At depth Z_p , the direction of flow reverses and what was once a downwards jet now rises as a buoyant plume in an annulus surrounding the original jet. This buoyant plume rises a distance H_p to the level of neutral buoyancy, at which point the flow intrudes into the body of the reservoir in the same qualitative way as for the bubble plume case. Calculation of the entrainment is a little more

complicated for a pump system compared to a bubble plume as the entrainment of ambient fluid can be expected to be governed by the equations for a jet-like flow between the bottom of the draft tube and the level of neutral buoyancy, a distance H_j , and as a buoyant plume over the distance H_p . For more detail regarding jet and plume dynamics, the reader is referred to Fisher et al. (1979).

The response of the thermal stratification in Googong Reservoir subjected to circulation by a draft tube mixer during spring and summer is illustrated in Figure 5 and under natural conditions in Figure 6. When the draft tube mixers are used, the water column between the surface and 18 m (t1800, Figure 5) warms continuously through January 2008. Under natural conditions, substantial warming below 10 m does not occur (Figure 6). Evidence of the change in penetration depth of the jet in response to the temperature difference is seen as rapid warming at a depth of 25 m in mid-December 2007 and at 29 m depth in mid-February 2008. What has happened is that passage of a cold weather front has decreased the surface layer temperature sufficiently to allow the jet to propagate to a greater depth where the temperature is approximately within 5 °C of the surface layer temperature. Use of the draft tube mixers did not produce a consistent difference in surface mixed layer depth during spring and summer but did reduce the resistance of the water column to intermittent deepening events and brought forward the seasonal overturn of the water column from mid-May to mid-March.

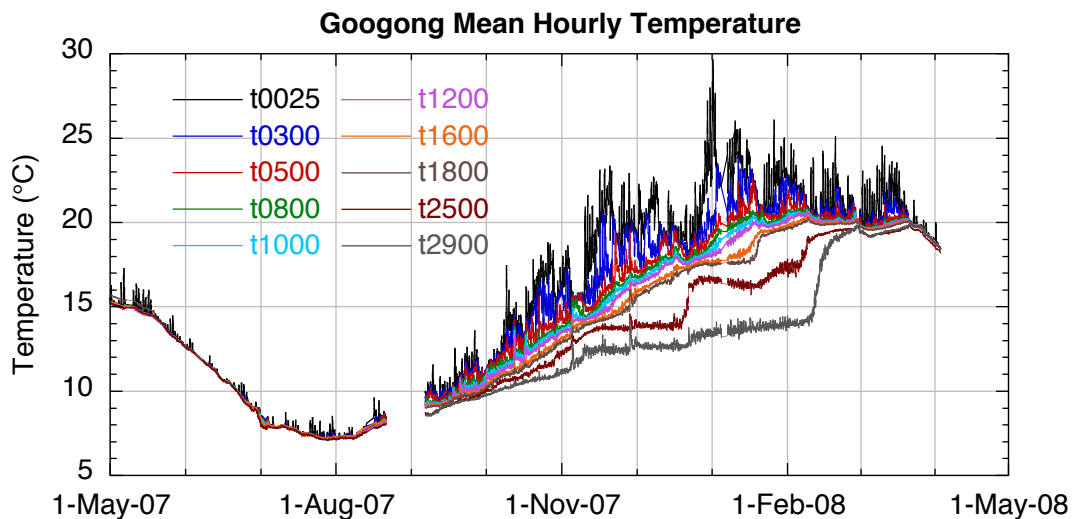


Figure 5. Evolution of thermal stratification in Googong Reservoir undergoing continuous circulation using a draft tube mixer. Lines show the temperature at 0.25, 3, 5, 8, 10, 12, 16, 18, 25, and 29 m depth. Figure from Sherman(2008).

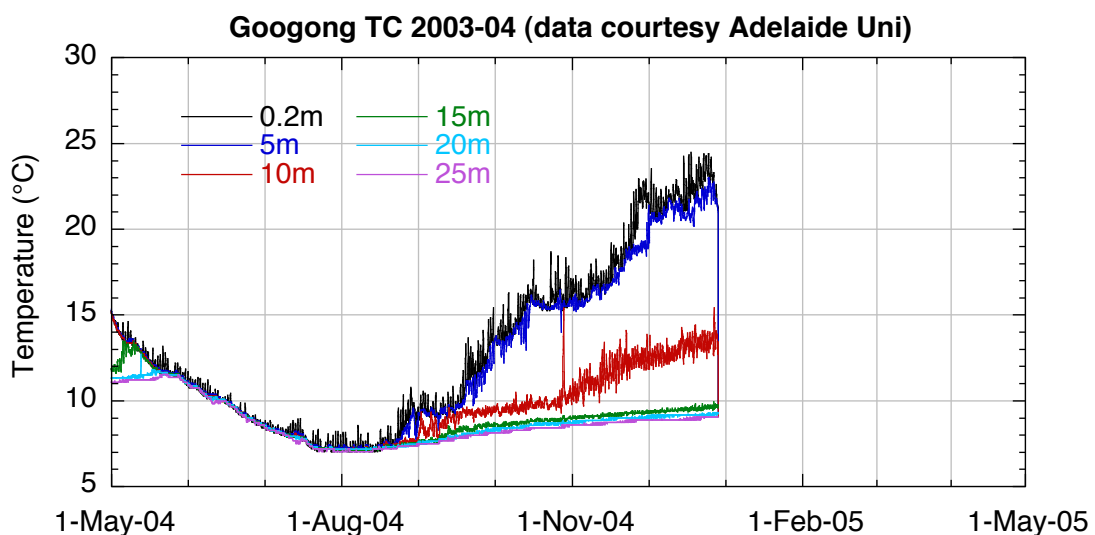


Figure 6. Evolution of thermal stratification in Googong Reservoir under natural conditions. Lines show the temperature at 0.2, 5, 10, 15, 20, and 25 m. Figure from Sherman(2008).

3. THE DESTRATIFICATION - EVAPORATION REDUCTION HYPOTHESIS

The hypothesis that artificial destratification can reduce evaporation is built upon the assumption that destratification will transport heat downwards from the surface layer faster than the sun can warm it up during spring and summer. Compared to natural conditions this results in colder surface layer temperatures during spring and summer and warmer temperatures during autumn and winter. For destratification to produce an annual reduction in evaporation, the reduction in evaporation rate during spring and summer must exceed the increase in evaporation that occurs during autumn and winter.

The evaporative flux from a water surface is dependent upon the difference in vapour pressure between the air just above the air-water interface and the atmosphere above. At the interface, the air can be assumed to be saturated with moisture at the temperature of the water surface. In the atmosphere above, the vapour pressure can be determined from the relative humidity and the air temperature. This flux can be estimated using some form of bulk aerodynamic formula such as (Fischer et al., 1979):

$$E = CU(p_{v\ sat} - p_{v\ air})$$

where C is a constant determined empirically, U is the wind speed, $p_{v\ sat}$ is the saturated vapour pressure in air at the temperature of the water surface, and $p_{v\ air}$ is the vapour pressure in the air where wind speed, air temperature and humidity are nominally measured at 10 m height. More elaborate bulk formulae that take into account atmospheric stability (Liu et al., 1979) are typically used in reservoir hydrodynamic models.

Because the moisture carrying capacity of air increases rapidly with air temperature (Figure 7), a relatively modest reduction in surface layer temperature can reduce the vapour pressure difference sufficiently to produce appreciable reductions in the evaporative flux. For example, assuming an atmosphere with temperature of 25 °C and relative humidity of 50 %, a reduction in the water surface temperature from 25 to 23 °C would reduce evaporation by more than 20 % for a given wind speed. Of course, an increase in surface temperature such as typically occurs during autumn and early winter will increase the evaporation rate above natural levels.

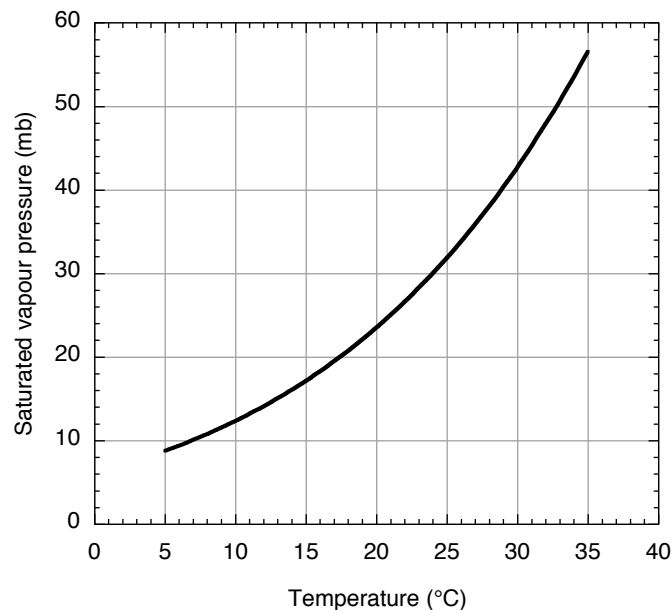


Figure 7. Saturated vapour pressure as a function of air temperature.

3.1. Heat Fluxes that Affect the Temperature of the Surface Layer

The water column of a reservoir is exposed to a number of heat fluxes and the temperature of the surface depends intimately on these fluxes. Sensible (conduction) and latent (evaporation) heat fluxes exchange heat from the surface of the water column to the adjacent air just above the air-water interface. Short wave solar radiation penetrates down into the water column; the depth to which the light penetrates depends upon the optical properties of the water column. The more highly stained and the more turbid the water column, the shallower the light penetrates. It is often the case in Australian reservoirs that > 95 % of incoming solar radiation is absorbed within the surface mixed layer (SML) - the layer below the air-water interface that is actively mixing vertically². The SML in Australian storages is typically 3 - 5 m deep.

The last major heat flux is long-wave radiation (wavelengths 3 - 60 μm): downwelling long-wave radiation depends on atmospheric temperature and moisture content (including clouds) and may also depend on vegetation cover where a significant fraction of the sky is blocked by foliage. Finally, the water surface emits upwelling long-wave radiation and the strength of this flux varies as the 4th power of the water surface temperature ($^{\circ}\text{K}$). The strong increase in evaporation and long-wave emission as the water surface temperature increases places an upper limit on the temperature that any particular water body can experience when subjected to solar heating.

3.2. Carry-Over Heat Storage

Pumping heat down through the water column during spring and summer produces a large increase in the total heat stored in the water column at the onset of autumnal cooling and this stored heat ensures that the water surface temperature is higher than would be experienced during much of autumn and early winter. By mid-to-late winter the cooling of the reservoir is complete and the temperature of the well-mixed water column at this time will become the initial condition for the following year's heating. It is entirely possible that autumn-winter cooling will not reduce the temperature of a reservoir that has been destratified during the preceding spring and summer to the same level as was experienced under natural conditions.

Ultimately, the annual heat budget of a reservoir is governed by local climatic conditions and by the inflow and outflow regime of the storage. A destratified storage can be expected to approach a new quasi-equilibrium thermal condition consistent with these conditions (as will be shown in the following section). Hughes et al. (1975) (as cited by Van Dijk and Van Vuuren, 2009) used a modelling approach to examine the potential evaporation reduction from destratification and found that the heat flux of the outflow played an important role in the heat budgets of some storages.

The net annual heat flux due to inflows and outflows from a storage is likely to play an important role in determining whether or not destratification has the potential to produce a reliable annual reduction in evaporation.

² The surface mixed layer depth can be operationally defined using ten-minute average thermistor chain data (ten second sampling) as the depth of the thermistor below which the next thermistor reports a temperature at least 0.05 - 0.1 $^{\circ}\text{C}$ colder (Sherman et al., 2000; Sherman et al., 1998).

4. NUMERICAL SIMULATION OF POTENTIAL EVAPORATION REDUCTION

Numerical simulations of the impact of artificial destratification on evaporation were performed using two approaches. The first approach was to explore the theoretical sensitivity of annual evaporation to water column depth and the assumed initial temperature distribution in the water column using a one-dimensional reservoir hydrodynamic model, DYRESM. The second approach was to use the model ELCOM to undertake a full 3-dimensional simulation of the performance of the WEARS mixer system currently deployed and operating at Googong Reservoir near Canberra, ACT. Both models used bulk aerodynamic formulae corrected for atmospheric stability to compute air-water energy transfers.

Googong Reservoir was selected as the evaluation site because it currently undergoes artificial destratification using a state-of-the-art surface draft-tube mixer system and very high resolution meteorological data and thermistor chain data – measured on-site – were available for a full year (Sherman, 2008). In addition, underwater spectral attenuation data are available for the reservoir. These data allowed the most accurate possible model forcing of the surface energy transfers for both 1-D and 3-D models as well as critical assessment of the accuracy of the 3-D model's simulation of surface mixers.

All simulations were run for a period of one year. Ten-minute and fifteen-minute meteorological data measured with instruments deployed on a pontoon on the reservoir surface or located on land adjacent to the reservoir were aggregated into one-hour mean values. These data included downwelling short wave radiation, downwelling long wave radiation, air temperature, relative humidity, wind speed, wind direction and rainfall. Data from the pontoon-deployed meteorological station were used in preference to the adjacent land-based data when both were available. Thermistor chain data from four sites in the storage were available for comparison with the 3-D model results (Sherman, 2008) and were used for defining the initial temperature distribution (except for the 12.8 °C scenario which was defined by the results of the 8.4 °C scenario).

4.1. 1-D Simulation of Potential Evaporation Reduction

The one-dimensional Lagrangian reservoir model, DYRESM (Imberger and Patterson, 1981; Imberger et al., 1978), was used to perform the theoretical assessment of potential evaporation reduction as a function of water column depth. The water column was represented as a square vertical column with a cross-sectional area of 1 km². Apart from rainfall, no inflow or outflows were considered so that the model results reflect only the impact of complete water column mixing. Complete mixing was forced every model time step by specifying that sufficient energy was available to mix out the potential energy of any stratification that arose due to surface heat fluxes and the absorption of short wave radiation.

Six scenarios were considered (Table 1) for theoretical assessment of the maximum potential reduction in evaporation. Each scenario was run for four water column depths: 5, 10, 20, and 40 m. The runs, commencing on 1 Apr 2007, used the observed water column temperature profile (strongly stratified) and aligned with the actual initial operation of the mixer system at Googong Dam as well as the input meteorological data. For July-June scenarios, the initial water column was isothermal at 8.4 °C, corresponding to observations for that date. The final scenario employed an initial temperature of 12.8 °C, which was based on the final temperature profile simulated using the 8.4 °C initial condition. The July-June simulations required the observed meteorological data to be 'wrapped' such that observations from 4 Apr - 30 Jun 2007 were used for the corresponding dates in 2008.

Note that the April-March run has been included for illustrative purposes only. Under typical operating conditions, destratification of a reservoir would commence in early spring in order to provide any potential evaporation reduction benefit during spring and summer.

Table 1. Potential evaporation reduction scenarios simulated using a 1-D hydrodynamic model.

	Natural Stratification	Forced Mixing
1 Apr 2007 - 31 Mar 2008	x	x
1 Jul 2007 - 30 Jun 2008 $T_o = 8.4\text{ }^\circ\text{C}$	x	x
1 Jul 2007 - 30 Jun 2008 $T_o = 12.8\text{ }^\circ\text{C}$	x	x

To facilitate objective comparison of potential evaporation reduction, it is best to commence simulations with a well-mixed water column close to the time of the minimum winter water column temperature. For a specified set of meteorological data, the thermal dynamics of the system are expected to approach a quasi-steady state after some period. If the initial temperature stratification reflects the 'average' natural condition and the meteorological data are not substantially different from 'average' meteorological conditions then one would expect the modelled temperature profile after one year's simulation to be close to the initial condition - any departure from this would reflect a departure of the heat budget of the storage from equilibrium conditions.

If the final water column temperature is close to the initial temperature, then the energy budget results for that simulation will be representative of conditions that are most likely to be experienced over the long term. Defining the equilibrium condition in this way implies also that the water lost to evaporation is replaced by an equivalent amount of water at the final/initial water column temperature (recall that we are assuming the final temperature equals the initial temperature at equilibrium). In other words, at equilibrium the total heat content of the water column at the end of the simulation must equal that at the start of the simulation.

4.1.1. 1-D Simulation Results

The predicted annual evaporation from the 1-D simulations is shown in Figure 8. Solid lines denote forced mixing of the entire water column at each model time step - this is equivalent to assuming perfect and instantaneous destratification. The dashed lines show the evaporation when natural stratification is allowed to evolve. For all July-June simulations where the water column was ≤ 20 m deep, the maximum predicted reduction in evaporation was $< 2\%$ for fully mixed water columns as compared to the natural stratified case.

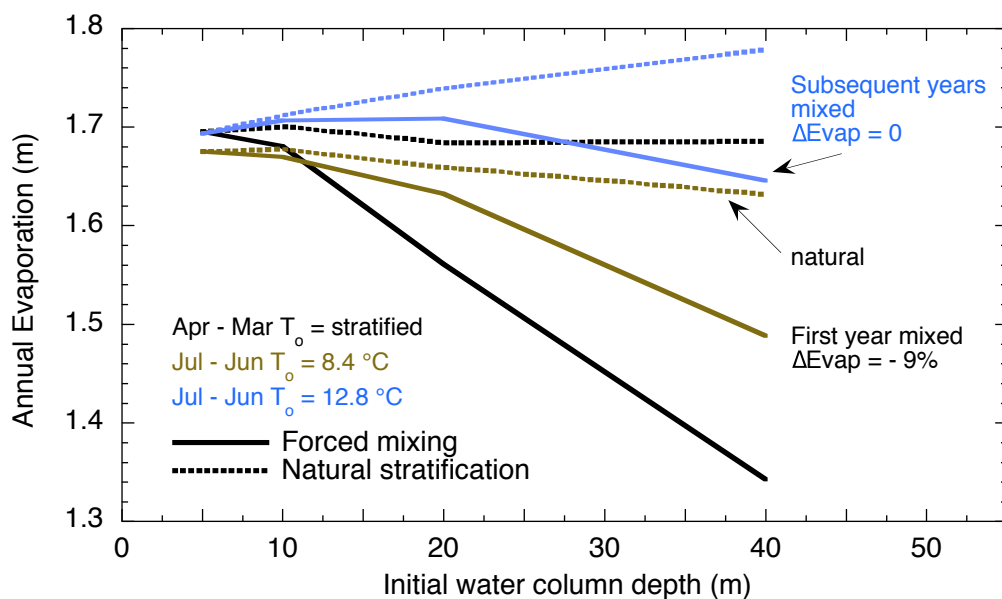


Figure 8. Results of 1-D simulation of potential reduction in evaporation assuming instantaneous complete mixing of the water column. Solid lines denote forced mixing. Dashed lines denote natural stratification. Black denotes simulation run starting 1 April with a stratified water column. Brown denotes simulation commenced 1 July assuming a mixed water column with uniform temperature of $8.4\text{ }^\circ\text{C}$. Blue denotes simulation commenced 1 July assuming a mixed water column with uniform temperature of $12.8\text{ }^\circ\text{C}$.

In contrast, the 40 m deep water column showed almost a 9 % reduction in annual evaporation when the water column was kept fully mixed. However, the 8.4 °C initial condition (brown lines in Figure 8) led to a final temperature 365 days later of 12.7 °C, showing that the system was not in thermal equilibrium over an annual time scale. When stratification was allowed to develop, the final water column temperature was 9.5 °C. When the initial temperature was set to 12.8 °C (blue lines in Figure 8 - effectively equivalent to running a second year of simulation), the final water column temperature was again 12.7 °C, implying that this simulation was close to the equilibrium condition. For the stratified case starting at 12.8 °C, the final water column temperature was 9.8 °C.

The April-March simulations (black lines, Figure 8) showed the greatest potential evaporation reduction because a large pool of cold water was instantly mixed into the surface layer.

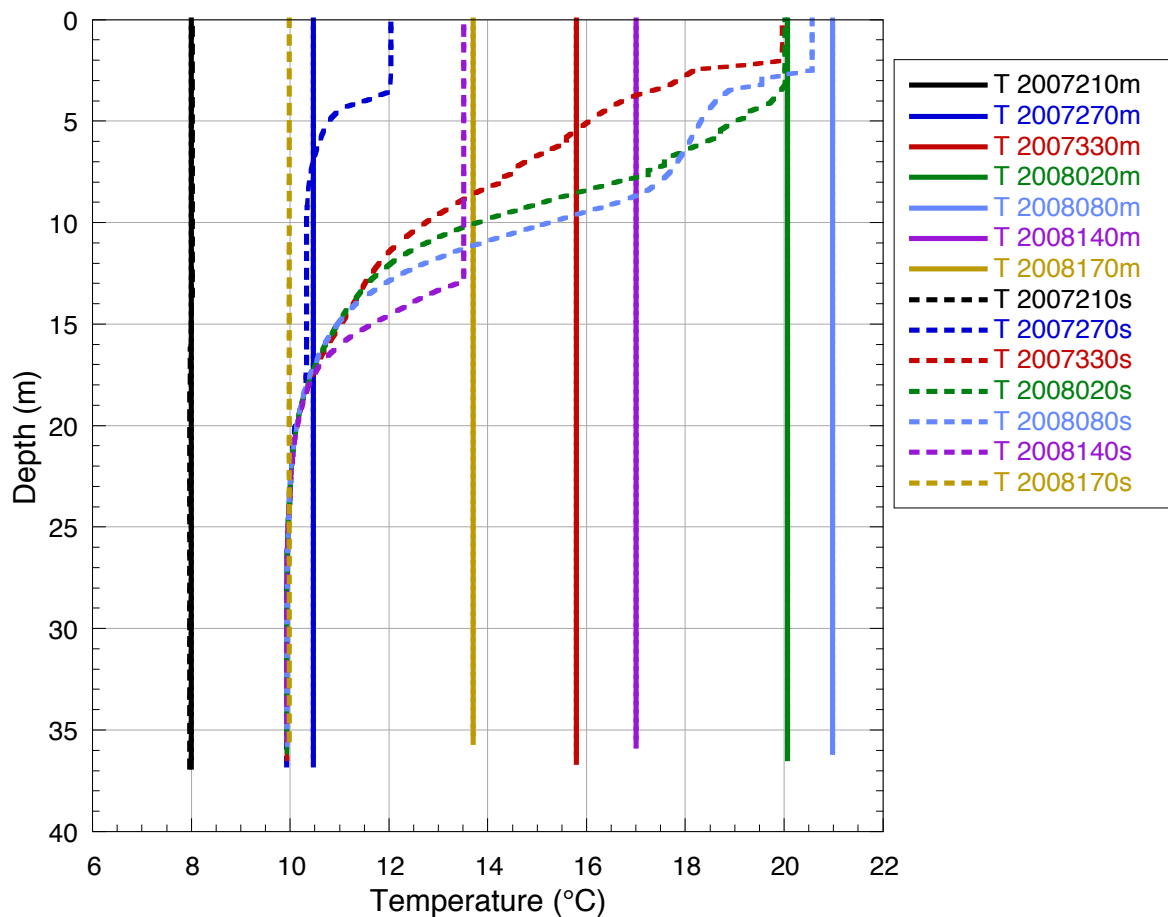


Figure 9. Simulated temperature profiles for 40 m water column. Date notation is yyyyddd where 2008001 = 1 Jan 2008. Solid lines show artificially destratified conditions. Dashed lines show stratified conditions. Simulation commences 2007182.

The evolution of the thermal stratification under mixed and stratified conditions is shown in Figure 9. Temperatures have departed after three months (2007270) with the onset of spring stratification. The mixed case experiences lower surface temperatures through January (2008020). Beginning in March (2008080) and continuing through the end of the simulation the mixed water column experiences progressively warmer surface layer temperatures compared to the natural stratification.

4.2. 1-D Simulation - Discussion

Under the quasi-equilibrium conditions believed to be most representative of the expected long-term impact of destratification, there is no appreciable difference in annual evaporation between artificially mixed (1.65 m of annual evaporation, blue solid line, Figure 8) and natural stratification conditions (1.63 m of annual evaporation, brown dashed line, Figure 8).

It is theoretically possible to displace the equilibrium condition by manipulating inflow and outflow volumes and temperatures. This was an important insight from the work of Hughes et al. (1975) (as cited by Van Dijk and Van Vuuren, 2009) and it implies that ultimately the potential reduction in evaporation accruing from destratification will depend upon other operational aspects of a storage. In this report, only the impact of destratification is considered - no allowance is made for inflow and outflow manipulation as this would require individual simulation of reservoirs on a case-by-case basis. In practical terms, this means that even if destratification does not produce an apparent benefit in terms of evaporation reduction under natural equilibrium conditions, it may still provide a reduction provided it is possible to replace enough reservoir water with sufficiently colder water to realise the benefit. In the example presented here, this could be thought of as withdrawing all the water from the 40 m water column at 12.8 °C and refilling it with 8.4 °C water. Whether or not this is feasible is clearly highly site-specific as it depends on temporal patterns of supply and demand relative to climatic conditions and the presence of stratified impoundments upstream.

4.3. 3-D Simulation Results

Googong Reservoir uses a large RESMIX (WEARS) circulation system consisting of 4 mixers, each with a nominal flow rate of $6 \text{ m}^3 \text{ s}^{-1}$. The mixers are deployed as two pairs of counter-rotating impellers and are operated continuously apart from possible short interruptions to the power supply. The system nominally discharges $24 \text{ m}^3 \text{ s}^{-1}$ through 4 x 6.1 metre-long draft tubes. The mixer system draws water from the top 1.3 m of the water column and discharges the water at a nominal depth of 8.5 m (the actual depth may vary slightly depending on the thrust of the system). The location of the mixers and the monitoring stations as well as the bathymetry of the reservoir are shown in Figure 10.

The model simulated the period from March 2007 to March 2008, corresponding to the period for which data were available to force the model and assess the accuracy of the thermal simulation. The ELCOM model provides two approaches for simulating the dynamics of the mixer: as a turbulent jet issuing vertically downwards; or as a buoyant plume issuing upwards from a specified depth which can be thought of as the penetration depth, Z_p , discussed previously (sec. 1.1). The turbulent jet representation of the system was found to provide the best comparison with the observed water column temperatures and was selected as the basis to compare mixed and un-mixed scenarios. In reality, the configuration is as shown in Figure 4, with both the level of neutral buoyancy and the penetration depth moving up and down relative to the draft tube in response to meteorological conditions. An exact numerical representation of the complete dynamics of the jet/plume system was not available in the model and should be considered for future development given the increasing number of draft-tube mixers in use today.

The model simulates the evolution of the temperature structure under destratified conditions reasonably well (Figure 11 and Figure 12). Surface layer temperatures are reproduced well as is the change in jet propagation distance following cold spells in December and February. However, the model predicted surface mixed layer depth was typically 3-4 m deeper than observed during the spring-summer stratified period and the surface layer temperature was typically 1-2 °C colder than observed. This bias in model-predicted surface layer temperature was observed in both mixed and un-mixed scenarios and appears to have arisen from a single inflow event early in the simulation (May 2007) and then propagated forward through the remainder of the simulation. The implication is that the absolute value of predicted annual evaporation will be less than observed but the comparison between mixed and unmixed conditions will be sound because the bias is a feature of both simulations. This highlights the sensitivity of hydrodynamic simulations to inflow heat fluxes; errors in inflow volume and temperature can have a profound effect on the reservoir's heat budget.

The ELCOM simulation computed evaporation under natural conditions to be 9000 ML. With the mixers running the predicted evaporation was 8700 ML, a reduction of 3% (Figure 13). This strongly suggests that the current design and operating criteria for draft tube mixers (and by implication, bubble plume systems), which typically address chemical water quality criteria, do not alter the temperature of the surface mixed layer of a reservoir sufficiently to produce an appreciable reduction in evaporation.

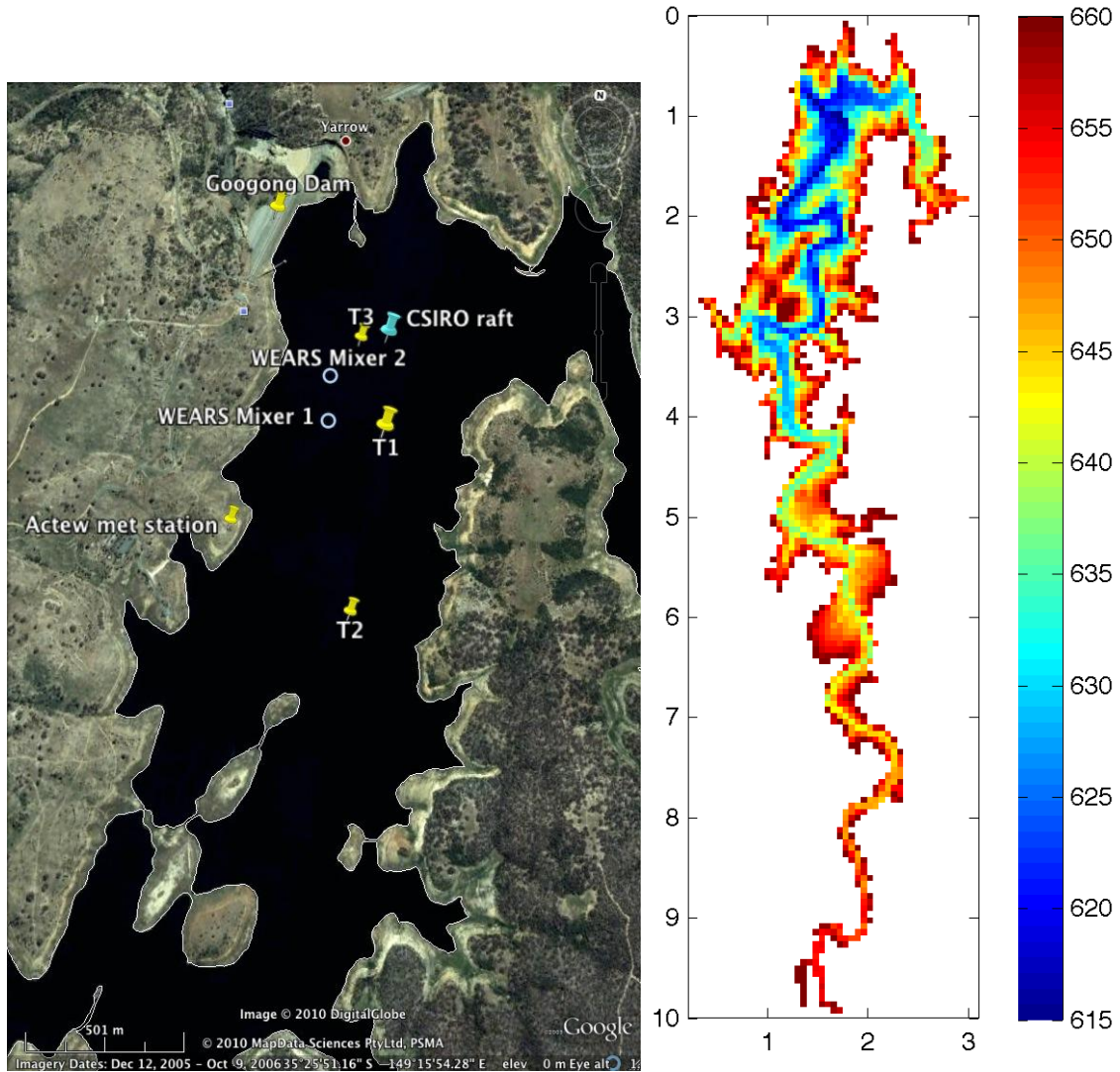


Figure 10. Main basin of Googong Reservoir showing location of WEARS mixers, thermistor chains (T1, T2, T3) and meteorological station (CSIRO raft), left. Bathymetry of Googong Reservoir (values are elevations AHD), right.

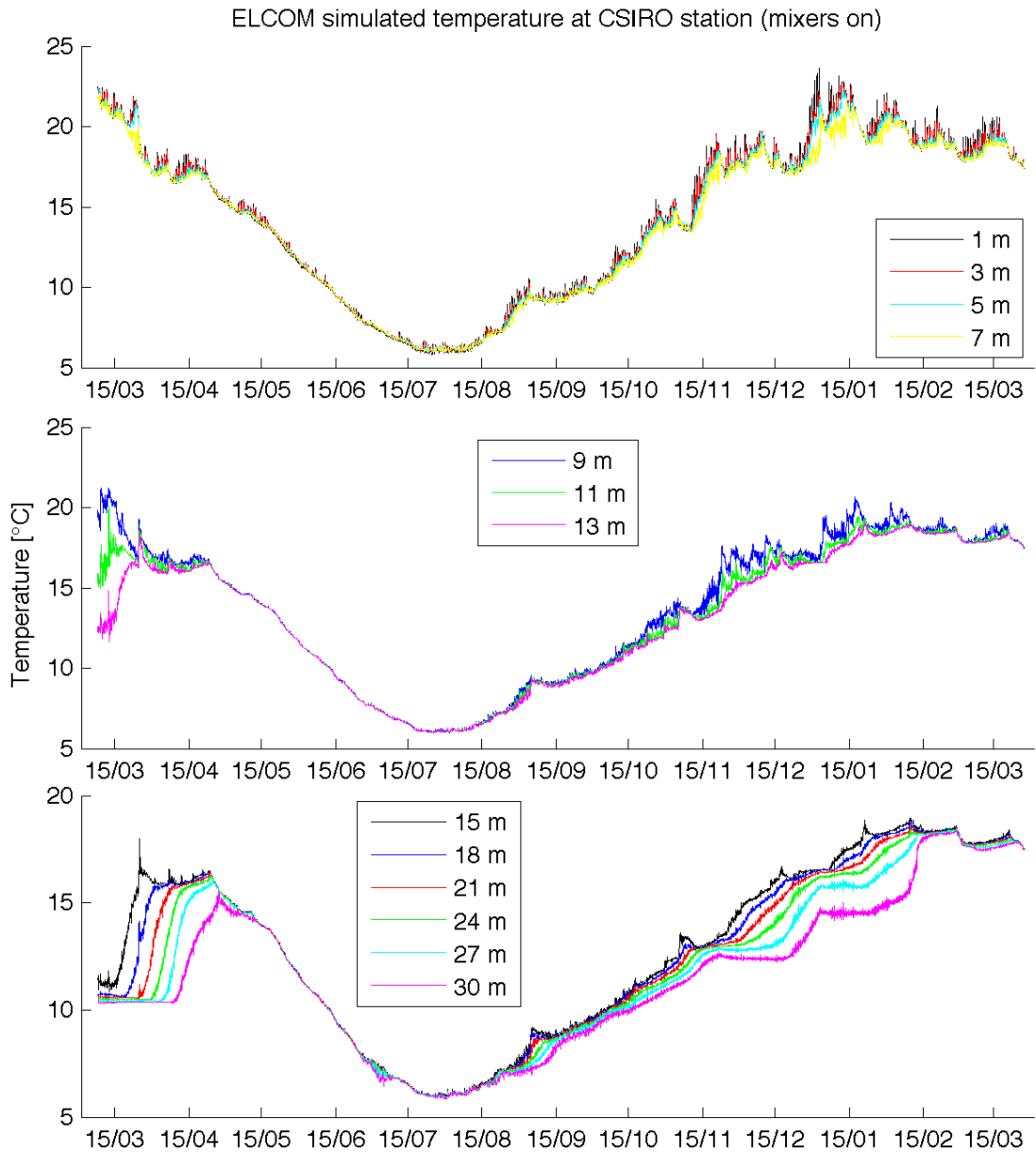


Figure 11. ELCOM simulated temperature at CSIRO meteorological station.

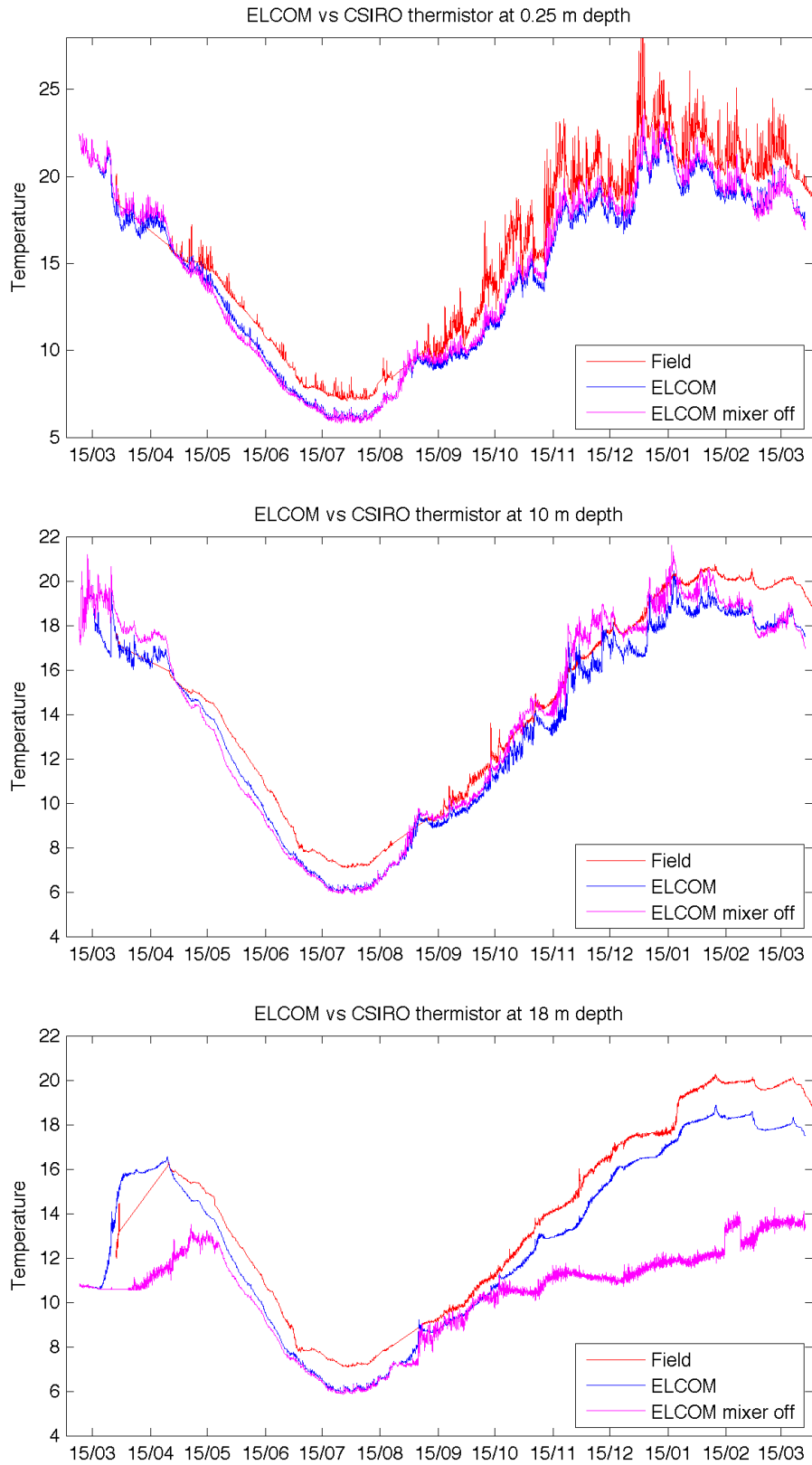


Figure 12. Comparison between observed temperatures at CSIRO thermistor chain in Googong Reservoir and ELCOM predicted temperatures at three depths: 0.25 m (top); 10 m (middle); 18 m (bottom).

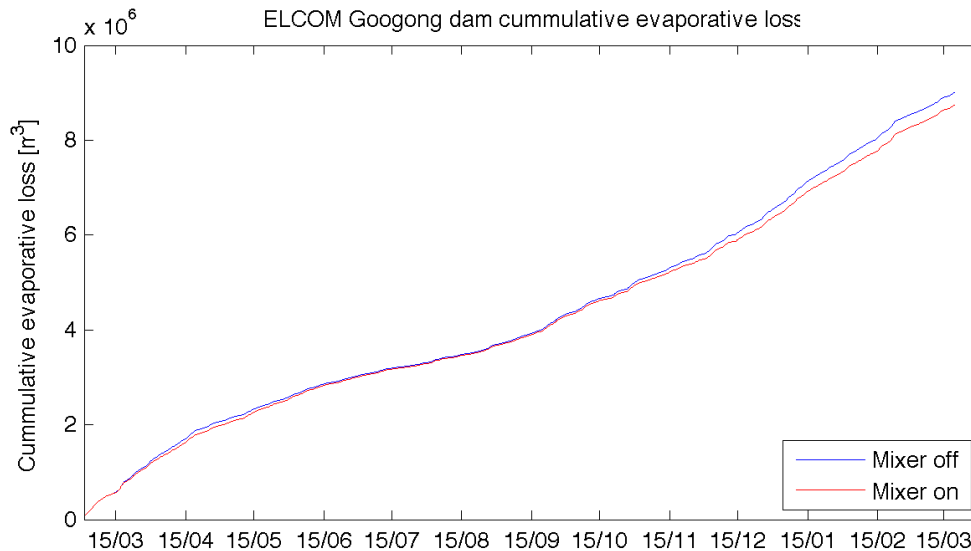


Figure 13. Cumulative evaporative loss from Googong Dam for mixer-on (destratified) and mixer-off (natural) scenarios.

5. CONCLUSIONS

Numerical modelling of the use of artificial destratification to reduce annual evaporation losses has shown no appreciable reduction in evaporation for water column depths < 20 m even given perfect instantaneous mixing of the water column. The modelling did predict some theoretical scope for reduced evaporation with a 40 m water column, but to realise the reduction in evaporation would require replacement of stored water with water several degrees colder. Such replacement might be possible to engineer depending on the timing and magnitude of inflow and outflow volumes and temperatures. Note that these results are based on a rectangular water column and that more natural bathymetry, including expanses of shallow areas and sheltered embayments removed from bubble plumes or mixers, would be less conducive to evaporation reduction. Should destratification be considered as a management strategy to reduce evaporation in deeper storages, it would be necessary to simulate the hydrodynamics of each specific system to test the feasibility of the strategy.

Direct observation of a large draft tube mixer system in Googong Reservoir shows little, if any, apparent reduction in surface layer temperature compared to a previous year without the mixer system operating. As a consequence, little impact on evaporation is expected to have occurred. These observations were confirmed by 3-D hydrodynamic modelling of the reservoir with and without the mixer system operating. This system is considered to be representative of current design practice and is one of the largest implementations of such a system yet undertaken.

In practice, the use of conventional destratification design principles appears unlikely to produce the change in surface layer temperature required to produce appreciable reductions in evaporation. Conventional designs are typically aimed to address chemical water quality issues related to low dissolved oxygen and are not capable of providing the instantaneous mixing upon which the theoretical reduction in evaporation is premised. In order to provide performance in the field that is close to the theoretical predictions for deeper storages, significantly greater capital investment (more mixers or plumes dispersed more widely) would be required to provide the circulation enhancement necessary to increase the downwards transport of heat.

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