Experimentally determined evaporation at varied water temperatures

WRL TR 2024/28, April 2025

By D M Gilbert, F C Chaaya and B M Miller

UNSW Water Research Laboratory

UNSW SYDNEY

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1 Introduction

Thermal stratification is a phenomenon that occurs in many natural and artificial waterbodies. The process of thermal stratification typically occurs during the summer months, when higher air temperatures and increased solar radiation heat the surface layer of the reservoir at a greater rate than in winter. This can cause the reservoir to separate into distinct thermal layers, due to warmer water possessing a lower density than cooler water. These layers are known as:

- Epilimnion – The surface layer which receives most of the thermal energy and is thus warmer and less dense than the hypolimnion.
- Hypolimnion – The bottom layer which receives less thermal energy and is cooler and more dense than the epilimnion.
- Metalimnion – The typically thin layer between the epilimnion and hypolimnion which features a pronounced temperature and density gradient called the thermocline. The thermocline acts as a barrier which restricts vertical mixing between the upper epilimnion and lower hypolimnion.

Bubble plume artificial destratification systems can be used to artificially promote vertical mixing and prevent thermal stratification (Chaaya & Miller, 2022). These systems breakdown or prevent the formation of a thermocline, resulting in a more homogenous temperature throughout the depth of a reservoir. This means that the surface temperature of the destratified reservoir will be changed, potentially affecting evaporation rates and thus water losses in the reservoir. Net water savings from artificial destratification were theoretically demonstrated in a previous desktop study (*WRL2022049 LR20231005, see Appendix B*) using numerically modelled surface temperatures from Pindari reservoir, located in NSW. The study also recommended the collection of evaporation rates from controlled water bodies with different surface temperatures to experimentally demonstrate the theoretically determined reduced evaporation rates.

As such, the Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney was requested by the NSW Department of Primary Industries and Regional Development – Fisheries (DPIRD Fisheries) to experimentally investigate the change in evaporation rates from a change in water surface temperature. The experiment aims to quantify the difference in evaporation from a change in water surface temperature that is expected due to the use of a bubble plume stratification system.

Evaporation rates were collected from two evaporation basins located next to each other and subject to the same meteorological conditions from July to November 2024, with one basin kept constantly 5 ^{o}C warmer than the other. This temperature difference was selected based on previous modelling work of Pindari reservoir (*WRL2022049 LR20231005*) which showed a 5 ^{o}C difference in surface water temperature between a stratified and unstratified reservoir. A single temperature difference was selected so that the experiment would be subject to a large range of different meteorological conditions. This report details the method and experimental findings.

2 Theoretical reduction in evaporation

2.1 Evaporation from open waterbodies

Evaporation from an open water surface is controlled by two primary mechanisms: heat and wind (Penman, 1948). Heat (energy) supplied to the surface through solar radiation and air temperature controls the vaporisation of water. Wind provides a mechanism for removing the vaporised water from the air-water interface. Excess heating and increased winds result in an increase in evaporation from a water surface.

Total evaporative water losses from a reservoir are intrinsically affected by the surface area of the reservoir. A larger surface area results in larger evaporative losses. The surface area to total capacity ratio of a reservoir will affect the total evaporative losses as a ratio of the total storage volume.

Artificial destratification is theoretically capable of reducing evaporation by reducing temperatures at the surface of the reservoir during the summer period. Decreased surface water temperature increases the latent heat of vaporisation of water, effectively increasing the energy required to vaporise water. Additionally, decreased surface water temperature decreases the saturated vapour pressure at the air-water interface. The difference between the vapour pressure at the water surface and the air above theoretically governs the evaporation rate, where a smaller difference (as a result of reduced surface water temperature) results in a lower evaporation rate (American Society of Civil Engineers, 1996). Surface water cooling through artificial destratification is likely to be more pronounced the deeper the reservoir is, due to the larger volume of water available for distribution of the heated water at the surface (Hefler et *al*., 2018).

However, artificially destratified reservoirs are typically warmer during the winter months compared to the stratified case. This is due to additional heat being stored throughout the entire depth of the reservoir in the destratified case, compared to the stratified case where heat is input to the shallow water column above the thermocline and vertical mixing is restricted. These higher temperatures in winter months can result in the destratified case having higher evaporation rates than the stratified case during the winter months, a reverse of the behaviour seen in summer months. This effect is greatest in deeper reservoirs, where cooling is delayed longer due to additional heat storage in the large volume of water. However, it is theorised that destratified reservoirs will still have a net reduction in evaporative losses over a year (see Section 2.3).

2.2 Estimation of evaporation

The aerodynamic method is commonly used to estimate evaporation from open water surfaces. Evaporation rates are theoretically determined based on the difference in vapour pressure at the temperature of the air and water surface (the vapour deficit), wind speed and a mass transfer coefficient (Penman, 1948; American Society of Civil Engineers, 1996), where:

$$E = 0.622 \times 86400 \times \rho_a \times \frac{C_E}{P} \times (e_s^0 - e_z) \times u_z$$

Where E is the estimated evaporation rate (mm/day), ρ_a is the density of air, $C_E = 0.0013$ is the bulk evaporation coefficient, P is the atmospheric pressure (Pa), e_s^0 is the saturated vapour pressure calculated using the surface water temperature (Pa), e_z is the vapour pressure of the air at height z (Pa), and u_z is the wind velocity at height z (m/s). Saturated vapour pressure, e_s^0, is calculated as (American Society of Civil Engineers, 1996):

$$e_s^0 = \exp\left(\frac{16.78T - 116.9}{T + 237.3}\right)$$

Where e_s^0 is the saturation vapour pressure (Pa) and T is the water surface temperature (°C). The vapour pressure of the air, e_z, is calculated as (American Society of Civil Engineers, 1996):

$$e_z = 0.01RH(e_z^0)$$

Where RH is the relative humidity and e_z^0 is the saturation vapour pressure at air temperature (°C).

Consequently, evaporation from an open body of water will decrease primarily as a result of:

- Decreased surface water temperature (until e_z exceeds e_s^0), increasing the vapour deficit
- Decreased air temperature compared to the surface water temperature, increasing the vapour deficit
- Decreased wind speed, effectively decreasing the removal of vapour from the air-water interface
- Decreased relative humidity, increasing the vapour deficit

Where surface water temperature data is unavailable, an assumption is often made that the surface water temperature is equivalent to the air temperature. This, however, limits the estimated change in evaporation due to the vapour deficit from changes in relative humidity. Conversely, available surface water temperature measurements or model predictions may not represent the temperature of the water at the very surface where evaporation occurs.

2.3 Previous studies

Artificial destratification has previously been investigated as a method of reducing evaporation losses from large bodies of water. These investigations commonly employed evaporation estimation techniques (simple calculations or developed models) to determine the potential evaporation savings based on reduced temperature at the surface of the reservoir. Early studies of the benefits of artificial destratification suggest that effective bubble plume destratification might reduce evaporation up to 15% (Koberg and Ford, 1965) under certain meteorological conditions. This study also demonstrated that, while artificial destratification resulted in reduced evaporation during warmer periods of the year (May to July, Northern hemisphere), it also resulted in increased evaporation during the following cooler months (September to November, Northern hemisphere). The additional heating throughout the reservoir resulted in delayed cooling at the surface of the reservoir during the natural turnover period, increasing evaporation during this period by up to 9%. More recent studies (e.g. Hefler et al., 2011; Hefler et al., 2018; Dijk and Vuuren, 2009) suggest destratification can achieve between 1 to 3% reduction in evaporative losses over a summer period. Evaporation reductions were suggested to be limited by reservoir depth, where larger reductions would be realised in a deeper reservoir.

A study previously performed by WRL (*WRL2022049 LR20231005, see Appendix B*) modelled evaporation in Pindari reservoir with and without destratification. Between 0 to 26% less evaporation was observed in the destratified reservoir during summer, however a 0 to 6% increase in evaporation was observed during the winter months. Over the course of a full year, modelling estimated that destratification would result in a mean decrease in evaporation of 6.5%. Assuming these rates were applied to the entire reservoir surface area, this would result in estimated water savings due to reduced evaporation of approximately 2,000 ML for Pindari reservoir at full supply level, and 1,000 ML at 50% reservoir capacity over a full year.

3 Method

3.1 Overview

The aim of this experiment was to provide experimental evidence to validate the claim that reducing the water surface temperature would result in less evaporative losses. This would consequently have water-saving implications for artificial destratification systems. The experiment consisted of two basins, with one of the basins constantly artificially heated to be 5 ^{o}C warmer than the other.

Previous work by WRL (*WRL2022049 LR20231005*) modelled Pindari reservoir with and without a destratification system, finding a maximum 5 ^{o}C difference in surface temperature. As such, this temperature difference was adopted for this study. However, it should be noted that this study does not aim to predict the evaporation savings of a destratification system at Pindari reservoir, but instead aims to confirm that a lower surface temperature results in less evaporative losses under environmental conditions. Evaporation is significantly influenced by climate conditions, leading to varying changes in evaporation rates due to the different surface temperatures anticipated in diverse climates.

Both a controlled laboratory experiment investigating evaporation at the micro surface and a more field-based evaporation experiment were considered. WRL adopted a field-based experiment to investigate whether the predicted evaporative savings could be achieved under more environmentally relevant conditions. Initially a local meteorological station was planned, however this was not achieved. Instead, experiments were conducted over a long time period (5 months) to capture a range of meteorological conditions.

3.2 Experimental setup

Evaporation experiments were conducted at WRL, located in Manly Vale, NSW. The setup consisted of two identical plastic basins, placed next to each other on a concrete slab (Figure 1). This was done so that all meteorological conditions influencing evaporation would be identical for the two basins. When full, the basins had a depth of 310 mm. Each basin was equipped with a floating thermistor to measure the surface temperature at 15 mm below the surface, and an ultrasonic sensor mounted to an aluminium frame above the basins to measure the water surface elevation. A 180 L/hour air bubbler was installed in each basin to provide mixing and achieve a constant temperature in each basin.

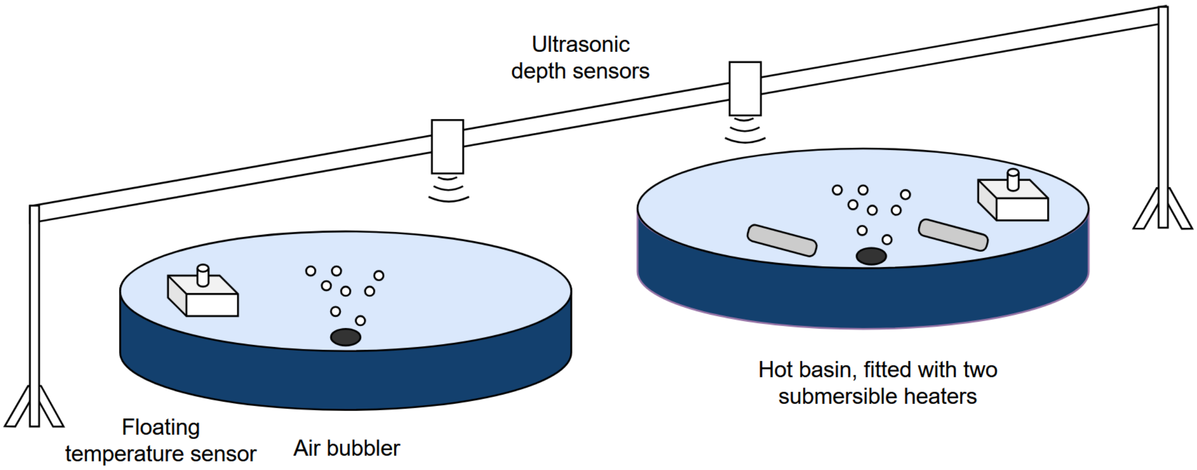

Figure 1 Experimental setup

One of the two basins was fitted with 500W of heating (with two submersible heaters, 200W and 300W respectively). A simple control system, shown in Figure 2, was programmed to maintain a 5 ^{o}C temperature difference between the two basins. Every 5 minutes the heater was turned on or off to maintain the temperature difference.

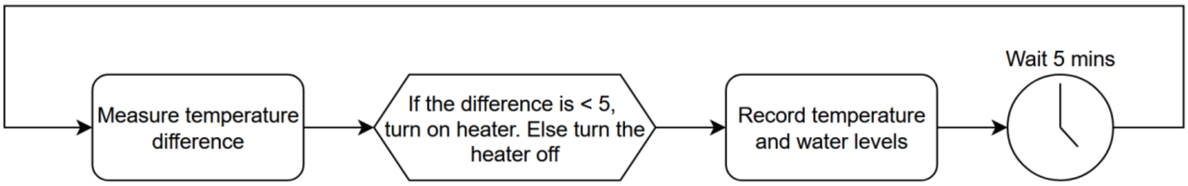

Figure 2 Logic for the temperature control system

3.3 Operation and data processing

The experiment began on 9 July 2024 and continued until 11 November 2024. During this period the basins were inspected twice a week and refilled roughly every fortnight, or when sensor maintenance was required. After 1 month of operation, the heating system was swapped from one basin to the other. This was done as a sensitivity test to ensure that the same evaporative behaviour was occurring in each basin.

A simple data processing step was conducted to break up the timeseries into periods of continuous evaporation. First, data was broken up whenever the basins were refilled, which occurred eight times throughout the experiment. Next, data during rainy periods was also removed, with a rainy period classified as more than a 5 mm increase in water level over 1 day. Poor quality data were also removed during September due to a faulty power supply, resulting in poor water level readings.

A final filtering step was then applied to each of the separate periods to remove any outliers in water level readings.

This resulted in 12 measurement periods with an average duration of 8 days, and a total experiment duration of 92 days.

4 Measured evaporation rates

4.1 Evaporation results

Measured evaporation rates across each continuous period (uninterrupted by rainfall, basin filling or faulty sensors) are summarised in Table 1. Weighted averages were also computed using the duration of each evaporation period to scale the metrics. These results show that the warmer basin had a statistically significantly higher evaporation rate ($P < 0.05$ for a paired t-test), with an average 3.5 mm/d increase in evaporation from a 5 ºC increase in surface temperature. This provides experimental evidence that reducing surface temperatures can reduce evaporative losses, which has potential water saving implications for thermal destratification systems. However, the exact change in evaporation rates will depend on the climate at the site and will likely vary from these values.

Table 1 Evaporation rate results

Start date	Duration (days)	Evaporation rate (mm/d)		Difference (mm/d)	R^2	
		Cold basin	Hot basin		Cold basin	Hot basin
09/07/2024	15	-2.1	-5.4	-3.2	0.99	1.00
28/07/2024	4	-1.2	-4.8	-3.6	0.70	0.97
02/08/2024	9	-1.4	-4.1	-2.8	0.94	0.99
14/08/2024	11	-2.0	-5.0	-2.9	0.97	0.99
28/08/2024	4	-4.4	-8.0	-3.7	0.98	0.99
12/09/2024	6	-4.1	-7.6	-3.6	0.98	0.99
27/09/2024	14	-3.1	-7.0	-3.9	0.96	0.99
11/10/2024	3	-3.6	-8.0	-4.3	0.94	0.98
15/10/2024	4	-2.4	-5.9	-3.4	0.89	0.97
18/10/2024	6	-4.8	-9.0	-4.3	0.98	0.99
24/10/2024	6	-5.5	-9.2	-3.7	0.99	0.99
31/10/2024	10	-2.9	-6.9	-4.0	0.94	0.99
Weighted average		-3.2	-6.7	-3.5		

4.2 Seasonal variations

Additionally, a slight but statistically significant ($P < 0.05$ for a paired t-test) increase in evaporation differences was observed between the cooler and warmer months of the year. Mean differences in evaporation between the basins were 3.2 mm/d in July to September and 3.9 mm/d in October to November. Figure 3 shows the mean increase in evaporation in the heated basin plotted against the average natural temperature (measured in the cold basin) over each of the 12 measurement periods.

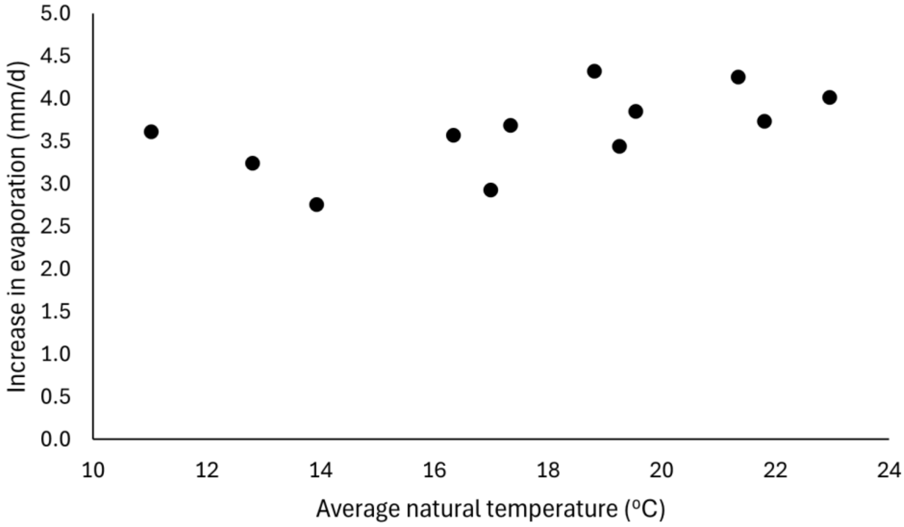

Figure 3 Increase in evaporation plotted against the average temperature in the cold basin (unheated) for each of the 12 measurement periods

The experimental evaporation rates were found to be highly linear with time within each time period, with an average R^2 value of 0.96 across both basins. This indicates that evaporation was highly consistent across each period, and supports the approach of adopting a single evaporation rate for each period, as shown in Figure 4. The second period (28/07/2024 start date in Table 1) had an anomalously low R^2 value of 0.70, however this is assumed to be due to the short measurement duration (4 days) and low amount of evaporation during this period (Figure A-2). Complete timeseries for each period are available in Appendix A.

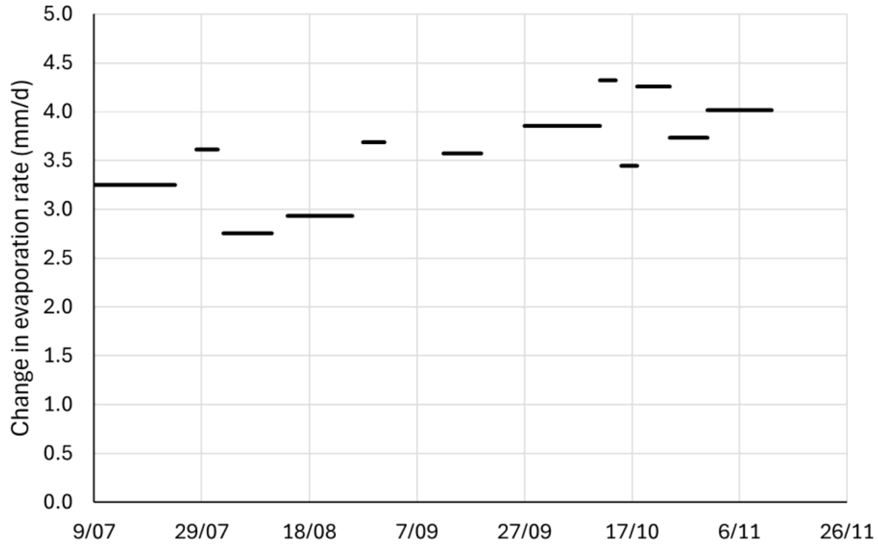

Figure 4 Change in evaporation rate from a 5 ºC surface temperature difference

4.3 Experiment limitations and potential future work

These results show that a 5 ºC difference in surface temperature resulted in an average reduction in evaporation of 3.5 mm/day under the conditions of the test. This value should be interpreted understanding the assumptions and limitations of this test before directly applying the value to a field site. Critically, it should be understood that the test was performed under meteorological conditions for the trial location (Manly Vale, NSW) and that conditions will be different at the field site. Further, the surface temperature reduction from a bubble plume destratification system will not remain constant at 5 ºC, meaning the evaporation reduction will also vary based on reservoir state, climate conditions and destratification design/operation. The temperature difference was achieved by increasing the temperature in one pan, as opposed to decreasing the temperature which would better represent the effects of a destratification system. While this was still valuable for obtaining indicative evaporation rates, there are expected errors associated with this due to the relative temperature difference between the water and air impacting evaporation. Further testing could be conducted with a range of temperature differences other than 5 ºC, to demonstrate the sensitivity of evaporation rate changes to the relative temperature difference.

Further, the laboratory trials were undertaken in a relatively shallow basin (310 mm deep when full), where the temperature close to the surface was measured and controlled. Whereas, in the field, there is uncertainty regarding how much bubble plume destratification systems will cool the very near surface layer due to microstratification effects. This raises two important considerations for a field trial:

- The decrease in very near surface temperatures of the reservoir should not be assumed to be the same as deeper in the water column.
- During field trials of a destratification system, temperature measurements should also be taken at the very near surface (say 30 cm below) to allow for research into microstratification.

The methodology from this study could be extended to a field site to obtain a site-specific measure of evaporation differences. Additionally, options also exist to float evaporation pans on the surface of a reservoir to measure evaporation based on meteorological conditions directly affecting the reservoir surface (at the location of the pans). However, there would still be variability from the climate conditions during the test, and the reservoir state. Furthermore, the surface temperature change from destratification may vary across the reservoir surface, and multiple surface temperature measurement points may be required to make a detailed assessment of water savings using this method.

5 Conclusion

A total of 92 days of evaporation rates from two basins were collected over a period from July to November 2024. One of these basins was artificial heated to maintain a constant water temperature 5 ^{o}C warmer than the other.

The data collected shows an increase in evaporation in the artificially heated basin, resulting in an average 3.5 mm/d of additional evaporation. These results provide experimental evidence that increased surface water temperatures result in increased evaporation, and therefore lowering the surface water temperature would decrease evaporation rates.

As such, artificial destratification systems have the potential to achieve water savings by reducing the surface water temperature during the warmer summer months. However, the exact evaporation rates and change in evaporation rate will depend on the climate and may vary from the values measured in this report.

Furthermore, destratified reservoirs are typically warmer during the winter months, meaning they may have higher evaporative losses during these periods. Site specific studies should be performed to determine the net saving in evaporation from a destratification system.

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Appendix A Water level timeseries

Processed water level timeseries data is presented in Figure A-1 to Figure A-13.

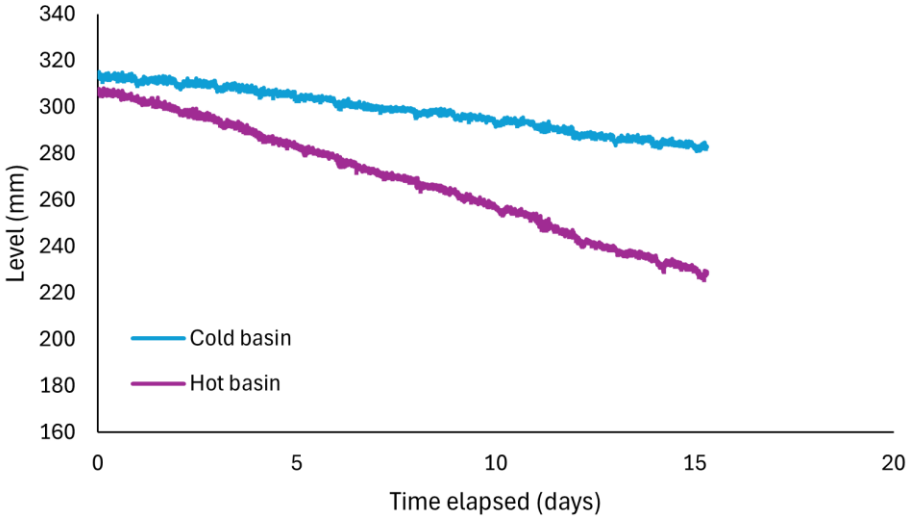

Figure A-1 Evaporation from 09/07/2024 to 24/07/2024

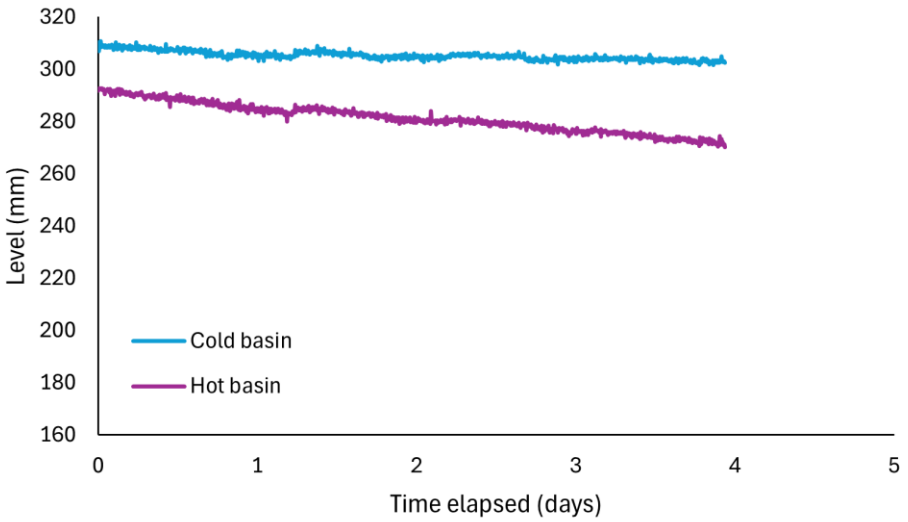

Figure A-2 Evaporation from 28/07/2024 to 01/08/2024

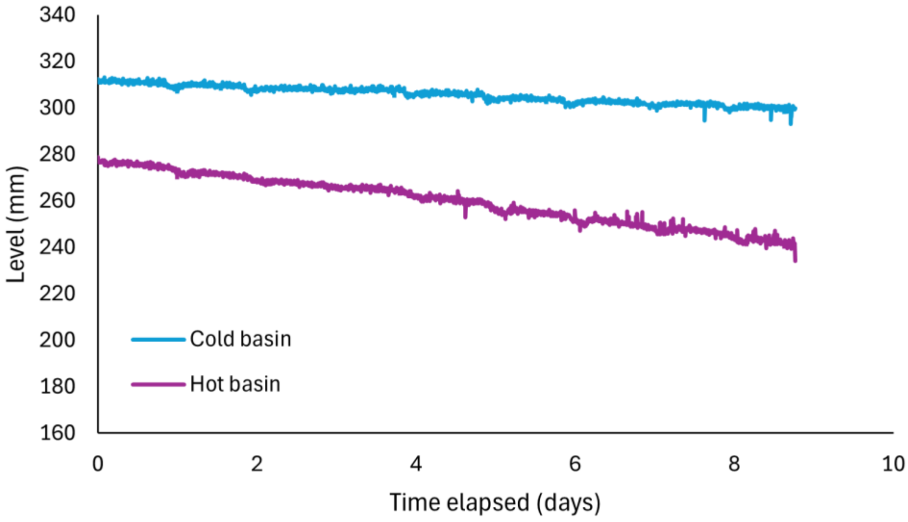

Figure A-3 Evaporation from 02/08/2024 to 11/08/2024

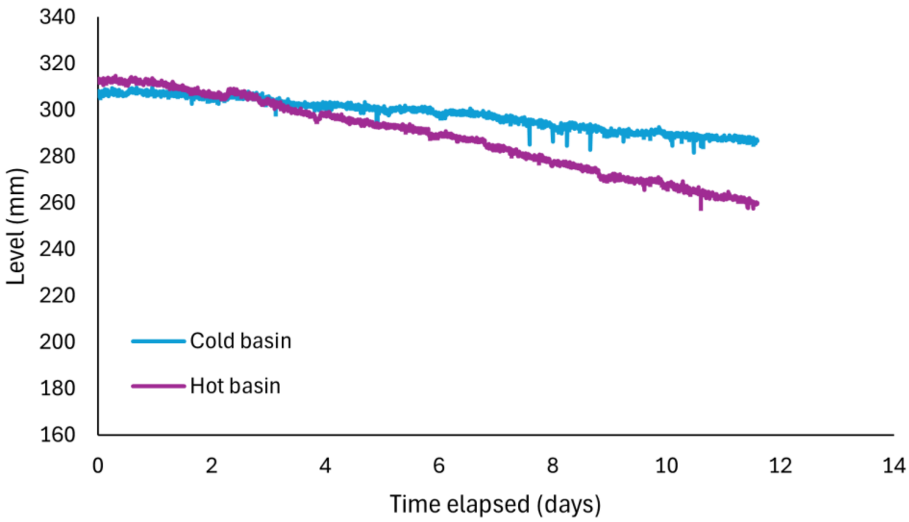

Figure A-4 Evaporation from 14/08/2024 to 26/08/2024

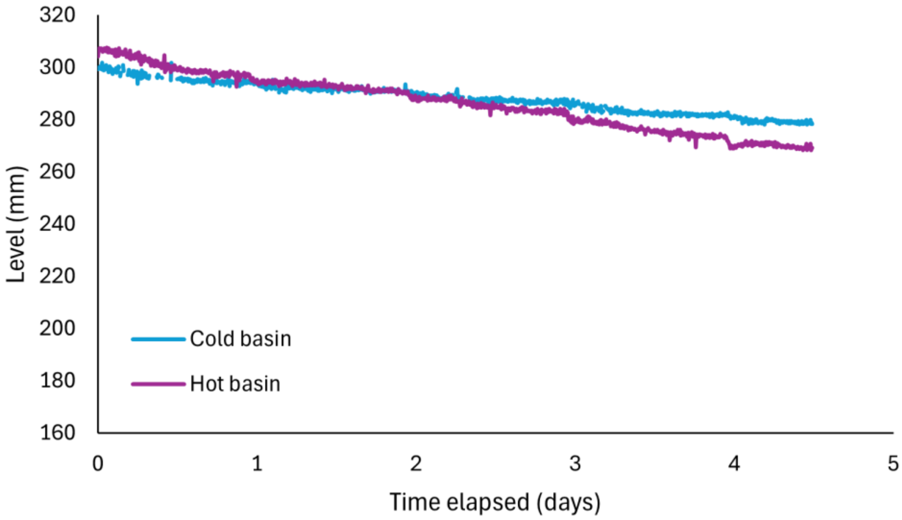

Figure A-5 Evaporation from 28/08/2024 to 01/09/2024

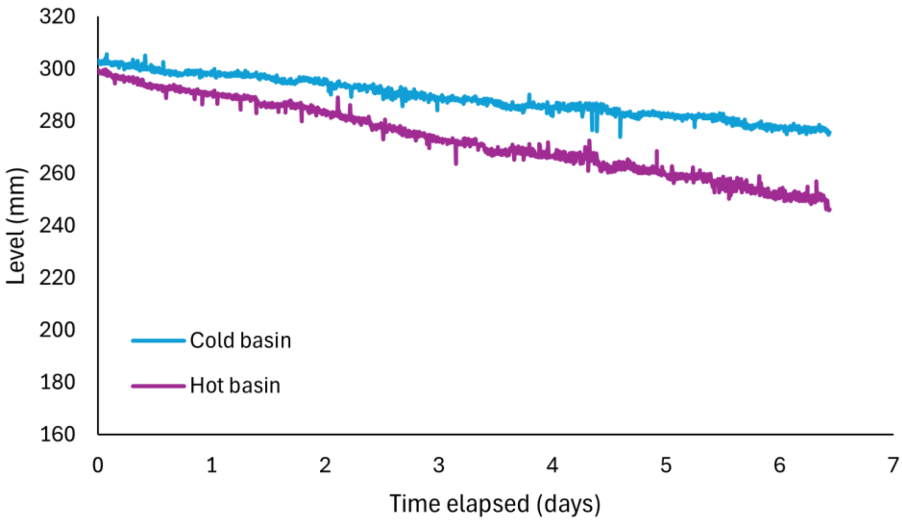

Figure A-6 Evaporation from 12/09/2024 to 19/09/2024

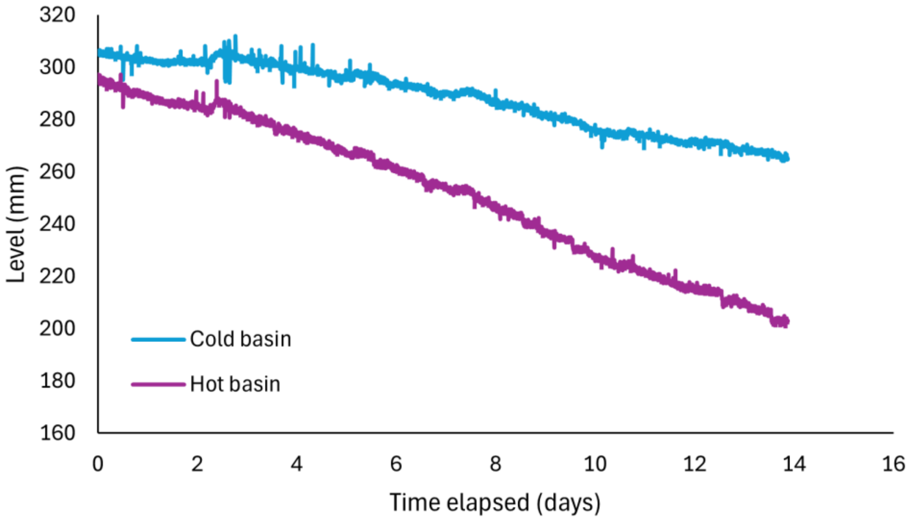

Figure A-7 Evaporation from 27/09/2024 to 11/10/2024

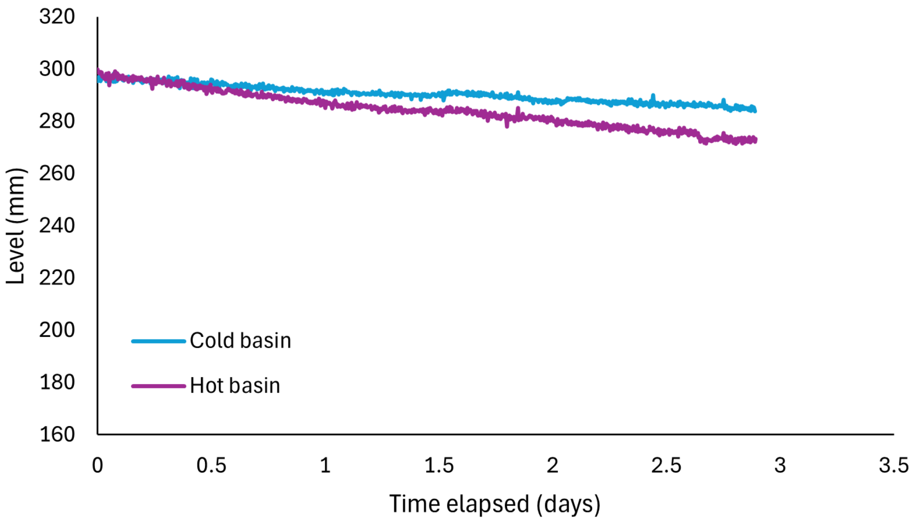

Figure A-8 Evaporation from 11/10/2024 to 14/10/2024

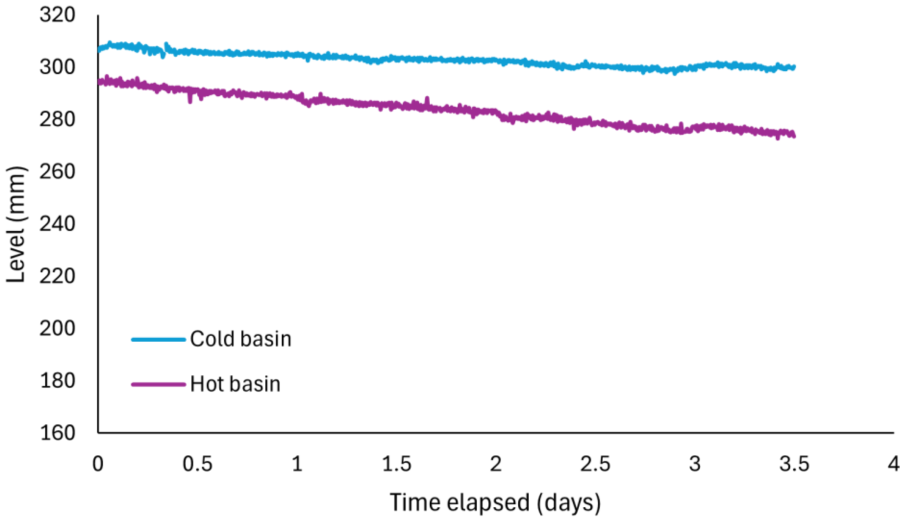

Figure A-9 Evaporation from 15/10/2024 to 18/10/2024

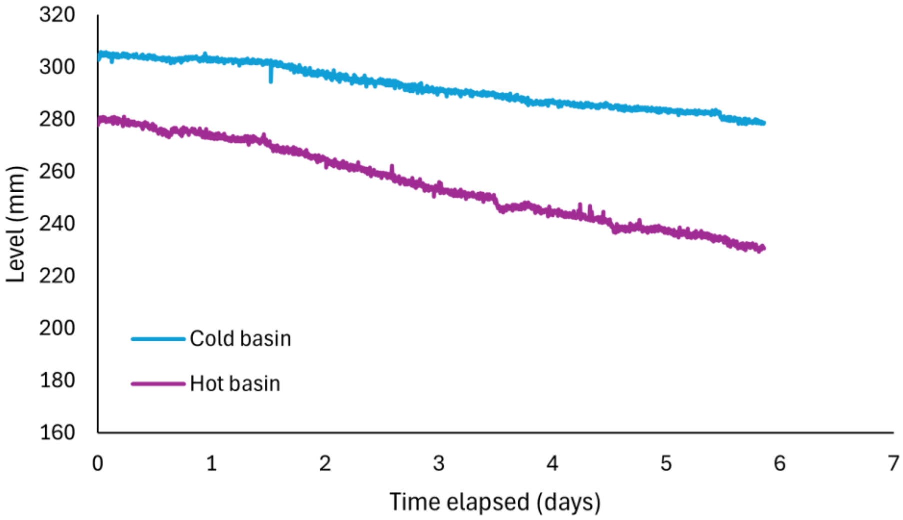

Figure A-10 Evaporation from 18/10/2024 to 24/10/2024

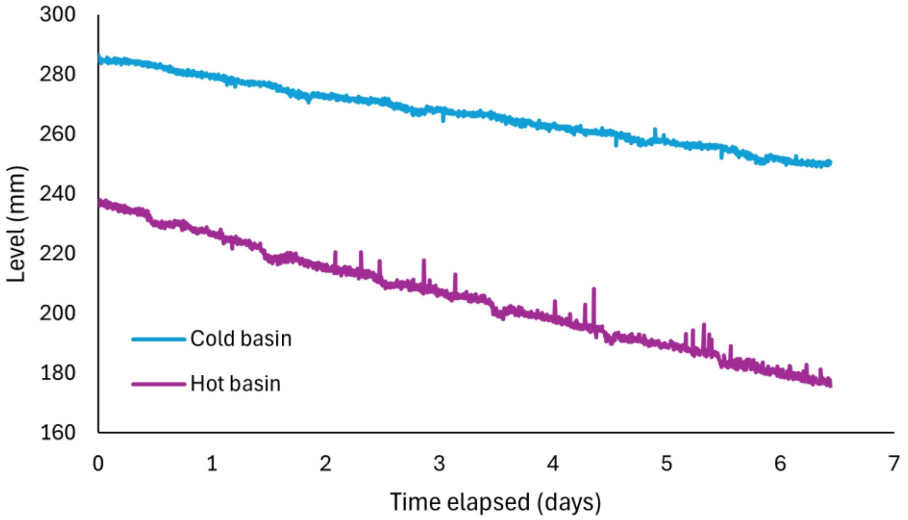

Figure A-11 Evaporation from 24/10/2024 to 31/10/2024

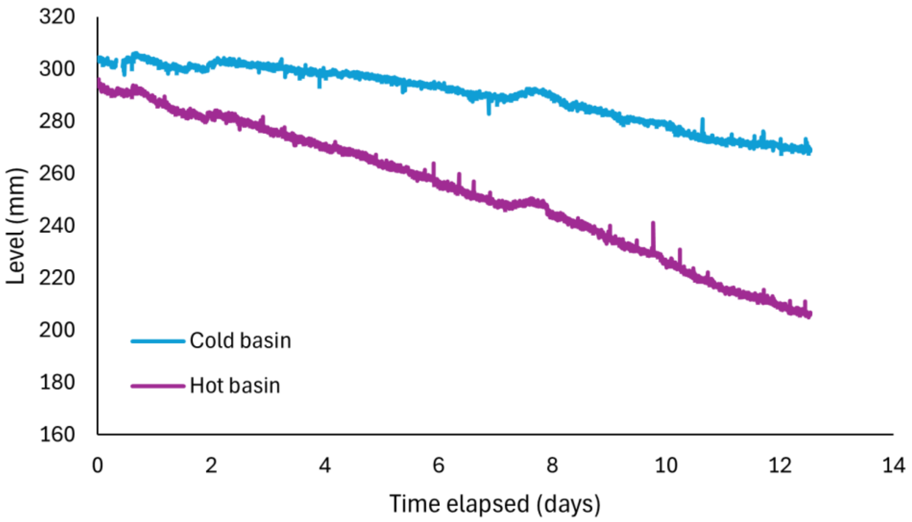

Figure A-12 Evaporation from 31/10/2024 to 12/11/2024

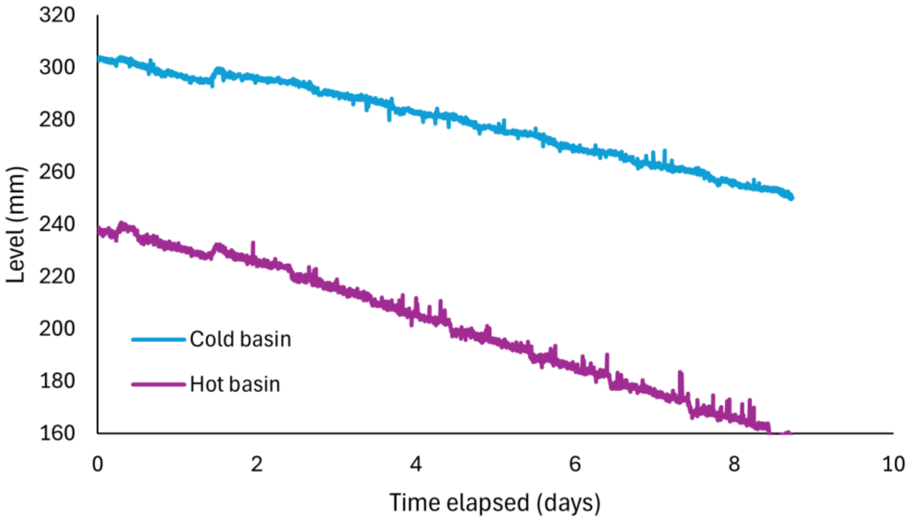

Figure A-13 Evaporation from 17/11/2024 to 26/11/2024

Appendix B *WRL2022049 LR20231005*

5 October 2023

WRL Ref: WRL2022049 LR20231005 BMM

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UNSW Water Research Laboratory

Dear Matthew,

Potential water savings in large reservoirs resulting from artificial destratification

1. Introduction

The Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney was requested by the NSW Department of Primary Industries – Fisheries (DPI Fisheries) to investigate the potential water savings that might be achieved through bubble plume artificial destratification of large reservoirs. These savings would be realised through reduced evaporation at the surface of the reservoir.

2. Theoretical reduction of evaporative losses

2.1 Stratification and artificial destratification

Large storage reservoirs thermally stratify during summer periods due to increased air temperatures and solar radiation. This stratification results in high surface temperatures and cooler temperatures lower in the water column. Bubble plumes are a form of artificial destratification as discussed in Chaaya and Miller (2022).

Artificial destratification is a process that mixes the reservoir resulting in uniform (or near uniform) temperatures throughout the water column. This results in cooler waters at the surface compared to the reservoir without artificial destratification during summer.

The total heat entering the destratified reservoir during summer is greater than a stratified reservoir due to the cooler surface water absorbing more of the short-wave radiation. Additionally, the total heat stored in the reservoir is increased through destratification as warm surface waters are distributed through the entire water column. This in turn results in warmer waters at the surface during winter compared to the reservoir without artificial destratification.

2.2 Evaporation from open water surfaces

Evaporation from an open water surface is controlled by two primary mechanisms: heat and wind (Penman, 1948). Heat (energy) supplied to the surface through solar radiation and air temperature controls the vaporisation of water. Wind provides a mechanism for removing the vaporised water from the air-water interface. Excess heating and increased winds result in an increase in evaporation from a water surface.

Total evaporative water losses from a reservoir are intrinsically affected by the surface area of the reservoir. A larger surface area results in larger evaporative losses. The surface area to total capacity ratio of a reservoir will affect the total evaporative losses as a ratio of the total storage volume.

Artificial destratification is theoretically capable of reducing evaporation by reducing temperatures at the surface of the reservoir during the summer period. Decreased surface water temperature increases the latent heat of vaporisation of water, effectively increasing the energy required to vaporise water. Additionally, decreased surface water temperature decreases the saturated vapour pressure at the air-water interface. The difference between the vapour pressure at the water surface and the air above theoretically governs the evaporation rate, where a smaller difference (as a result of reduced surface water temperature) results in a lower evaporation rate (American Society of Civil Engineers, 1996). Surface water cooling through artificial destratification is likely to be more pronounced the deeper the reservoir is, due to the larger volume of water available for distribution of the heated water at the surface (Hefler et *al*., 2018).

A reservoir that was artificially destratified during a summer period will have greater evaporation in the subsequent winter period due to the additional heat stored in the reservoir. This additional heat, compared to the naturally stratified case, will delay cooling at the surface of the reservoir in late autumn and winter. This may result in increased evaporation compared to that which would occur if the reservoir was naturally stratified and heating was limited to the shallow water column above the thermocline. During this period, an increased reservoir depth is likely to further delay cooling due to the additional heat stored.

2.3 Previous studies

Artificial destratification has previously been investigated as a method of reducing evaporation losses from large bodies of water. These investigations commonly employed evaporation estimation techniques (simple calculations or developed models) to determine the potential evaporation savings based on reduced temperature at the surface of the reservoir. Early studies of the benefits of artificial destratification suggest that effective bubble plume destratification might reduce evaporation up to 15% (Koberg and Ford, 1965) under certain meteorological conditions. This study also demonstrated that, while artificial destratification results in reduced evaporation during warmer periods of the year (May to July, Northern hemisphere), it results in increased evaporation during the following cooler months (September to November). The additional heating throughout the reservoir resulted in delayed cooling at the surface of the reservoir during the natural turnover period, increasing evaporation during this period by up to 9%. More recent studies (e.g. Hefler et *al*., 2011; Hefler et *al.*, 2018; Dijk and Vuuren, 2009) suggest destratification can achieve between 1 to 3% reduction in evaporative losses over a summer period. Evaporation reductions were suggested to be limited by reservoir depth, where larger reductions would be realised in a deeper reservoir.

While it is likely that destratification of a stratified reservoir will result in a reduction in evaporation, the realised savings will be highly variable based on meteorological conditions and the surface area of a reservoir.

3. Theoretical estimations of evaporation

The aerodynamic method is commonly used to estimate evaporation from open water surfaces. Evaporation rates are theoretically determined based on the difference in vapour pressure at the temperature of the air and water surface (the vapour deficit), wind speed and a mass transfer coefficient (Penman, 1948; American Society of Civil Engineers, 1996), where:

$$E = 0.622 \times 86400 \times \rho_a \times \frac{C_E}{P} \times (e_s^0 - e_z) \times u_z$$

Where E is the estimated evaporation rate (mm/day), ρ_a is the density of air (eq. 4.15 in HH), $C_E = 0.0013$ is the bulk evaporation coefficient, P is the atmospheric pressure (Pa), e_s^0 is the saturated vapour pressure calculated using the surface water temperature (Pa), e_z is the vapour pressure of the air at height z (Pa), and u_z is the wind velocity at height z (m/s). Saturated vapour pressure, e^0, is calculated as (American Society of Civil Engineers, 1996):

$$e^0 = \exp\left(\frac{16.78T - 116.9}{T + 237.3}\right)$$

Where e^0 is the saturation vapour pressure (Pa) and T is the water surface temperature (°C). The vapour pressure of the air, e_z, is calculated as (American Society of Civil Engineers, 1996):

$$e_z = 0.01RH(e_z^0)$$

Where RH is the relative humidity and e_z^0 is the saturation vapour pressure at air temperature (°C).

Thus, evaporation from an open body of water will decrease primarily as a result of:

- Decreased surface water temperature (until e_z exceeds e_s^0), increasing the vapour deficit
- Decreased air temperature compared to the surface water temperature, increasing the vapour deficit
- Decreased wind speed, effectively decreasing the removal of vapour from the air-water interface
- Decreased relative humidity, increasing the vapour deficit

Where surface water temperature data is unavailable, an assumption is often made that the surface water temperature is equivalent to the air temperature. This, however, limits the estimated change in evaporation due to the vapour deficit to changes in relative humidity. Conversely, available surface water temperature measurements or model predictions may not represent the temperature of the water at the very surface where evaporation occurs.

4. Modelled evaporation reductions

For the purposes of quantifying potential evaporation reductions through artificial destratification, AEM3D was used to model surface water temperatures in a reservoir under two scenarios: naturally stratified and artificially destratified conditions. For the purposes of this assessment, a previously established model of Pindari reservoir was run from 1 September 2016 to 30 June 2017. The resulting surface temperatures from the two scenarios were used to compare predicted evaporation with the abovementioned aerodynamic method.

Evaporation change was calculated on a daily basis as the (destratified evaporation – stratified evaporation) / (stratified evaporation). Between the start of October and the end of April evaporation change was between 0% to -26% with a mean change of -13.5%. In the cooler months (from approximately the start of May onwards), increased evaporation of up to 6% was observed. The mean value over a full year was -6.5%.

Figure 4-1 presents the timeseries of hourly percentage evaporation change. Note, as an artifact of the aerodynamic equation used to estimate evaporation, 0 m/s wind speeds and 100% relative humidity result in an evaporation rate of 0 mm.

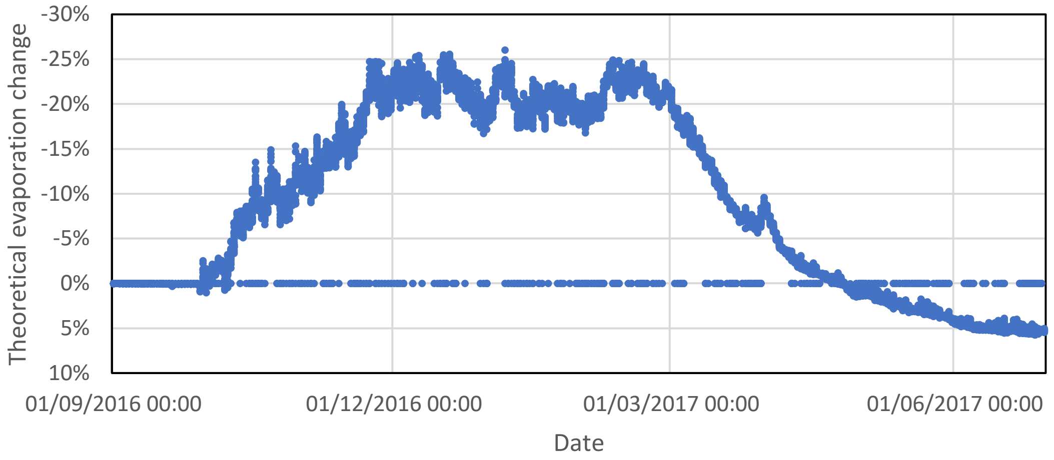

Figure 4-1 Timeseries of percentage evaporation change from stratified to destratified conditions

Figure 4-2 demonstrates the relationship between the difference in surface water temperatures and the percentage change in evaporation.

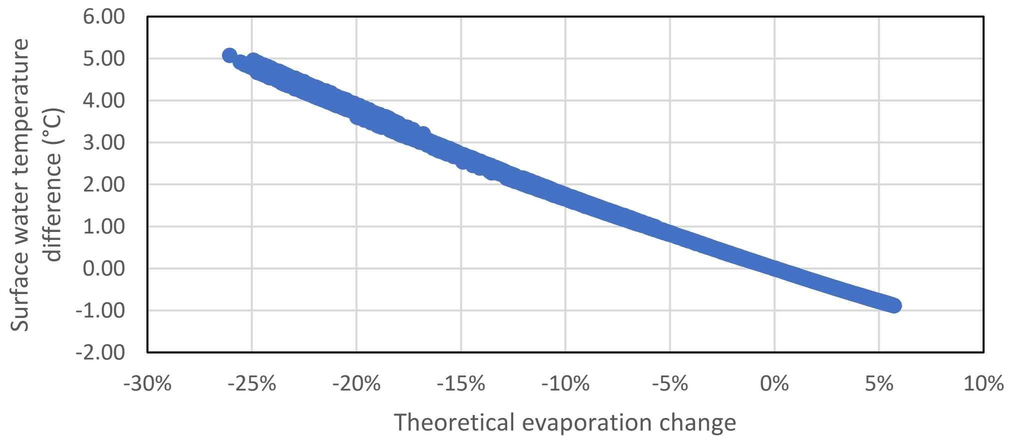

Figure 4-2 Evaporation change vs. surface water temperature difference

The clear relationship between the surface water temperature change and evaporation change highlights that any prediction of water saving from reduced evaporation are dependent upon measurement and prediction of surface water temperatures.

5. Volumetric evaporation estimations

The monthly evaporation change from stratified to destratified conditions was determined using the modelled evaporation changes presented in Figure 4-1. These monthly changes are shown in Figure 5-1.

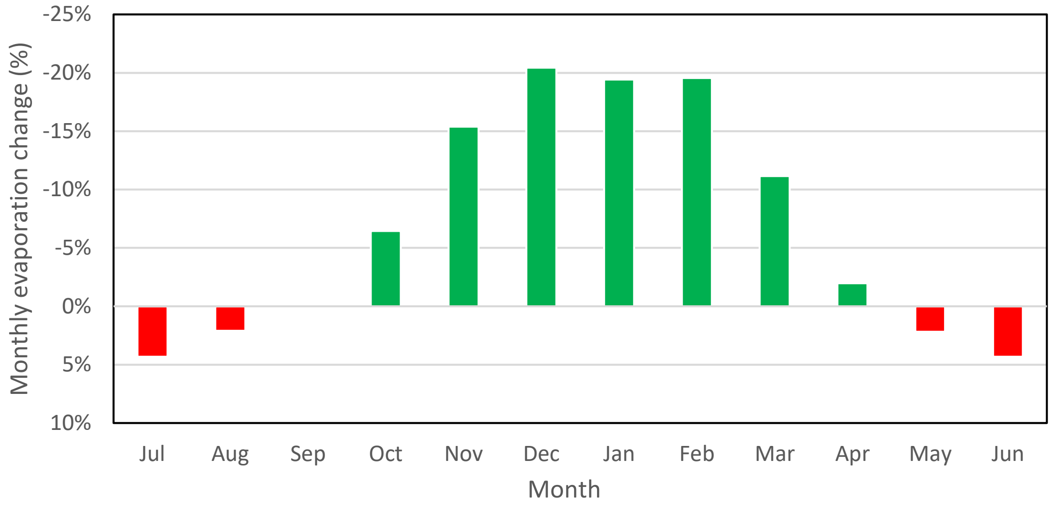

Figure 5-1 Monthly evaporation change from stratified to destratified conditions. Green indicates a reduction in evaporation, red indicates an increase in evaporation

A 10-year period of evaporation data between 1 July 2011 and 30 June 2021 was used to determine average monthly evaporation rates from Pindari reservoir (available through https://realtimedata.waternsw.com.au/water.stm). These monthly averages are shown Figure 5-2.

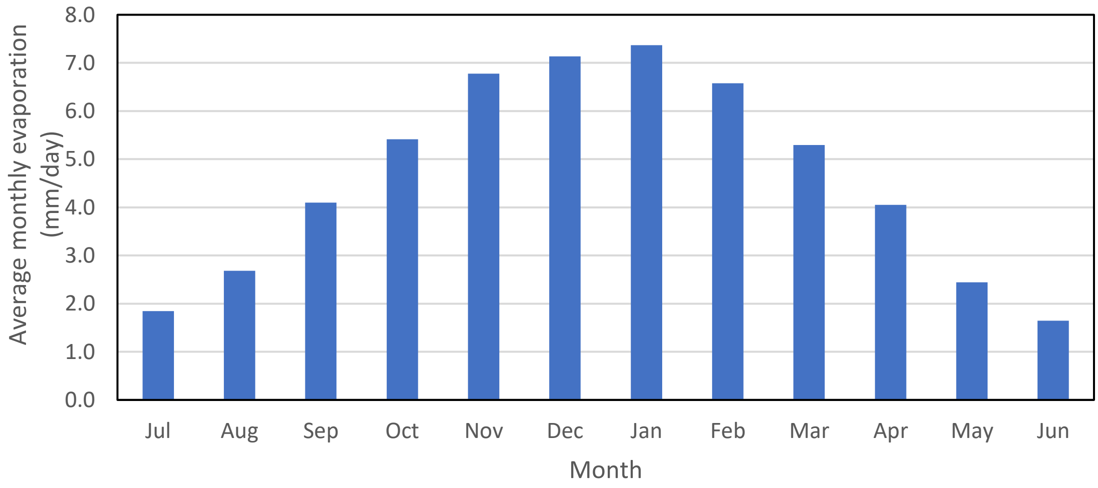

Figure 5-2 Average monthly measured evaporation at Pindari reservoir from 1/07/2011 to 30/06/2021

Volumetric evaporation from a reservoir can be determined as:

$$V = E \times A(S)$$

Where V is the volume evaporated, E is the evaporation rate and $A(S)$ is the surface area of the reservoir.

At 100% reservoir capacity (i.e. effective full storage, 312,000 ML), Pindari dam has a surface area of approximately 11 km^2. Using the average monthly evaporation rates measured at Pindari (Figure 5-2), the total volumetric evaporative losses from Pindari reservoir over a single year at 100% reservoir capacity is approximately 18,000 ML. Assuming the month-by-month evaporation changes presented in Figure 5-1, destratification would save 2,000 ML over the same period, through a net reduction in evaporation.

The Pindari reservoir bathymetry and available WaterNSW stage-storage data can be used to determine a relationship between the reservoir capacity (as a percentage of effective full storage volume) and surface area in Pindari reservoir. Figure 5-3 shows this relationship.

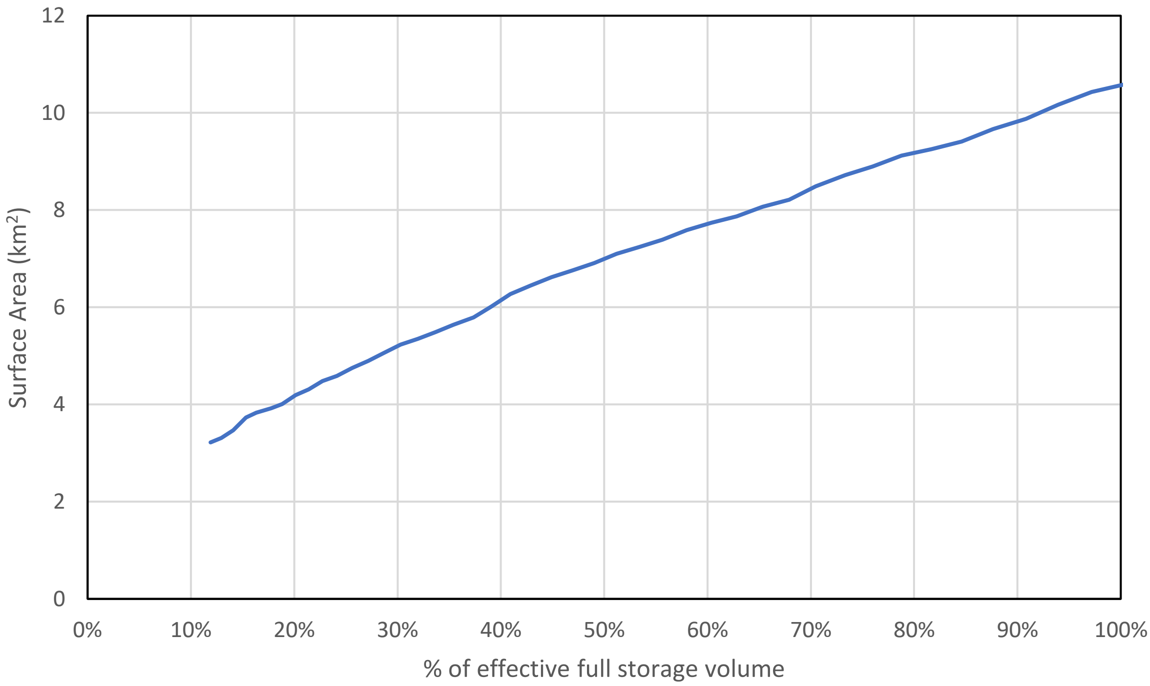

Figure 5-3 Relationship between surface area and reservoir capacity (as a percentage of effective full storage volume) for Pindari reservoir

At 50% reservoir capacity, the surface area of Pindari reservoir is reduced to approximately 7 km^2 (64% of the surface area at 100% capacity. The volumetric evaporative losses over a single year at 50% reservoir capacity would be approximately 11,000 ML. Destratification would result in a net reduction in evaporative losses of approximately 1,000 ML.

Values provided in this letter should be treated as estimates only and should be verified through fieldwork and further numerical modelling concentrating on near surface processes.

Experimentally measured evaporation rates using standard pan evaporation methods (American Society of Civil Engineers, 1996) under controlled water surface temperature conditions would provide greater confidence predictions. Ideally, this would measure evaporation from two identical standard Class A evaporation pans with different water temperatures.

Please contact Fred Chaaya or myself in the first instance should you wish to discuss the details raised in this letter further.

Yours sincerely,

Brett Miller
Director, Industry Research

6. References

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