Pindari Dam – mitigating cold water pollution through artificial destratification

WRL TR 2022/04, March 2023

By F C Chaaya and B M Miller

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1 Introduction

NSW Department of Primary Industry – Fisheries (hereafter referred to as DPI Fisheries) have been working with WaterNSW for many decades to investigate and implement solutions to cold water pollution downstream of large dams. Increased Summer air temperatures and solar radiation results in thermal stratification of large storage reservoirs. Stratification is known to cause temperature differences of more than 10°C between the surface and bed of a reservoir. Cold water pollution occurs when water is released from the lower part of a thermally stratified reservoir. The release of cold water results in a number of impacts to the natural downstream thermal regime, including:

- Significantly lowering summer temperatures in downstream rivers
- Reducing thermal amplitude in streams on a seasonal and daily basis
- Reducing the rapid rise in water temperatures that naturally occur in spring
- Delaying summer temperature peaks by weeks or months
- Sudden and severe temperature drops due to:
    - Large releases
    - Sudden changes to withdrawal depth (e.g. switching from spillway release to a deeper offtake)

To mitigate downstream cold water pollution, a reservoir must either be able to release surface (warmer) waters or be artificially mixed to ensure deeper waters are not as cold. A multi-level offtake (MLO) is required to selectively withdraw warmer water from near the surface of the reservoir. Not all NSW dams have a MLO. Those that do have demonstrated an ineffectiveness to mitigate cold water pollution due to conflicting algae management protocols.

The Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney was engaged by DPI Fisheries to conduct a review of cold water pollution mitigation strategies. The first phase of this work was to undertake an international literature review of artificial destratification techniques for cold water pollution mitigation (Chaaya and Miller, 2022). This report also provides background to cold water pollution, stratification and relevant reservoir mixing processes.

The literature review concluded that artificial mixing using bubble plume destratification was an option that could be successful in mitigating cold water pollution in NSW dams. This is discussed further in Section 2.2 of this report.

In parallel to WRL's investigations, the Australian Rivers Institute at Griffith University undertook numerical modelling trials of the destratification of Pindari Dam and Copeton Dam (Prentice *et al.*, 2021). WRL provided estimates of air flow and diffuser configurations for this modelling. This modelling provided confidence that bubble plume destratification was a viable option.

Originally this phase of WRL's investigations was to determine which of the NSW dams previously identified as priorities for cold water pollution mitigation should be selected for field trials. As work progressed, Pindari Reservoir emerged as appropriate for trials.

Specific to Pindari Dam, this report provides:

- A collation of existing data suitable to understand, quantify and model stratification and mixing.
- A gaps analysis of the existing data and recommendations of a monitoring strategy.

- An initial design for an operational destratification system for Pindari Dam.
- A preliminary cost analysis of capital and operational costs for the destratification system.

2 Summary of previous investigations

2.1 The NSW Cold Water Pollution Strategy

In response to the State Water Outcomes Plan that was developed under the *Water Management Act 2000* which contained requirements of water managers in NSW to address cold water pollution, the NSW Government adopted the NSW Cold Water Pollution Strategy. The Strategy was undertaken in two different stages: Stage One (2004 to 2009) and Stage Two (2010 to 2015). The Stage Two report indicated the intention to continue works through to a following stage, however a cessation of CWP Interagency Group meetings halted progress. As such, the NSW Cold Water Pollution Strategy remains unfinished.

WRL undertook a systematic review of the outcome reports from both stages, as well as any relevant literature that aided this 10-year project. The intended outcomes of the NSW Cold Water Pollution Strategy were:

- Recognising and prioritising dams causing severe CWP.
- Planning and implementing CWP mitigating infrastructure in priority dams.
- Developing and implementing operating protocols for dams with an existing MLO.
- Developing a governance framework and CWP Interagency group (CWPIAG).
- Implementing and maintaining a temperature monitoring network.

As part of Stage One of the NSW Cold Water Pollution Strategy, eight large NSW dams were outlined as priority for addressing cold water pollution:

- Burrendong
- Keepit
- Blowering
- Wyangala
- Copeton
- Hume
- Burrinjuck
- Pindari

WRL has provided a summary of the activities and outcomes of Stage One and Stage Two of the NSW Cold Water Pollution Strategy in Appendix A of this report.

2.2 International literature review

An international literature review of artificial destratification techniques for cold water pollution mitigation was undertaken by WRL (Chaaya and Miller, 2022). This review compared selective withdrawal strategies with artificial destratification strategies for mitigating cold water pollution. The literature review provides an in-depth review of the options, while a summary of the advantages and disadvantages of each strategy is provided in Appendix B of this report.

The literature review collated information on over 120 reservoirs where mechanical mixers or bubble plumes had been utilised for destratification.

From this, it was determined that bubble plume destratification would likely be the most effective strategy for mitigating cold water pollution in NSW reservoirs, considering the advantages and disadvantages of all strategies considered. In particular, destratification should theoretically be capable of reducing all the impacts of stratification both in and downstream of the reservoir, where selective withdrawal presents more of a downstream-focused approach. One of the more significant issues with selective withdrawal is the potential for cold shock to the downstream environment, which can have significant ecological impacts. Cold shock often occurs when intake depths are suddenly dropped to below the thermocline to avoid blue-green algae release downstream. The result is a significant volume of cold water being suddenly introduced to a previously naturally warm downstream river, the shock of which can result in wide-spread fish mortality.

2.3 Australian Rivers Institute - Griffith University destratification modelling of Pindari and Copeton Dams

Australian Rivers Institute at Griffith University undertook numerical modelling trials of the destratification of Pindari Dam and Copeton Dam concurrent to the WRL literature review. The numerical modelling studies for both Copeton and Pindari dam using the AEM3D numerical model (https://www.hydronumerics.com.au/software/aquatic-ecosystem-model-3d). The studies investigated the feasibility of modelling the onset of stratification in reservoirs based on meteorological and hydrological inputs followed by the artificial destratification using a bubble plume system.

For each reservoir, model scenarios considered:

- Baseline conditions of natural stratification.
- Bubble plume destratification based on 6-day and 30-day operation in mid-summer.
- Continuous bubble plume destratification commencing prior to the onset of stratification.
- Intermittent operation.
- The stratification occurring after a potential bubble plume malfunction.

WRL provided initial calculations of airflow rates to be tested. The modelling scenarios identified:

- Bubble plumes with an adequate airflow rate are capable of destratifying large reservoirs.
- Bubble plume destratification is potentially most cost effective when operation commences prior to the onset of stratification.

The modelling made use of available in-reservoir data however several broad assumptions were necessary for the modelled scenarios. The report highlighted that a monitoring network would be necessary for effective and efficient bubble plume destratification.

3 Pindari dam

3.1 Suitability for a destratification trial

Originally, this phase of WRL's investigations was to determine which of the NSW dams previously identified as priorities for cold water pollution mitigation should be selected for field trials. These dams were (Preece, 2004):

- Burrendong
- Keepit
- Blowering
- Wyangala
- Copeton
- Hume
- Burrinjuck
- Pindari

As work progressed, Pindari Dam emerged as the most appropriate for a destratification trial for the following reasons:

- The dam already has a multi-level offtake (MLO) which will allow for comparison of destratification and selective withdrawal CWP mitigation strategies.
- The destratification trials may require the bubble plume system to temporarily or intermittently cease operation to assess the impacts on the reservoir. The existing MLO would provide a temporary CWP mitigation option in these scenarios to minimise their downstream ecological effects.
- The reservoir has the smallest capacity of the above mentioned, high priority dams. Energy requirements will be proportional to reservoir capacity, making Pindari Dam a more economically feasible site for trials.
- While the capacity is smallest, the reservoir is still relatively deep (max. 73 m) which is an important pneumatic issue to be overcome in a bubble plume system. Also with a relatively deep system, the trial can test the theoretical potential for a destratification system to also mitigate algae issues.
- The reservoir is the most northerly which will have the hottest conditions over summer. As such, Pindari has a strong potential for stratification.
- The Australian Rivers Institute at Griffith University had already undertaken modelling scenarios of Pindari.

Pindari Dam was investigated during the NSW Cold Water Pollution Strategy. Upgrades to the existing multi-level offtake infrastructure were proposed as part of Stage One, however no works were undertaken due to the poor estimated benefit-cost ratio. In-lieu of these upgrades, existing operating protocols were revised and implemented over Stage One and Two of the NSW Cold Water Pollution Strategy. The new protocols made use of the selective withdrawal capabilities of the existing multi-level offtake to mitigate cold water pollution downstream of Pindari Dam by releasing water from the upper-most available inlet in the reservoir water column during periods of stratification.

3.2 Location

Pindari Dam is located in inland north-eastern NSW, close to the NSW-QLD border (Figure 1). The dam is situated on the Severn River, and supplies regulated flows for irrigation, stock, domestic, town water and industrial use along both the Severn and Macintyre rivers system (WaterNSW, 2021).

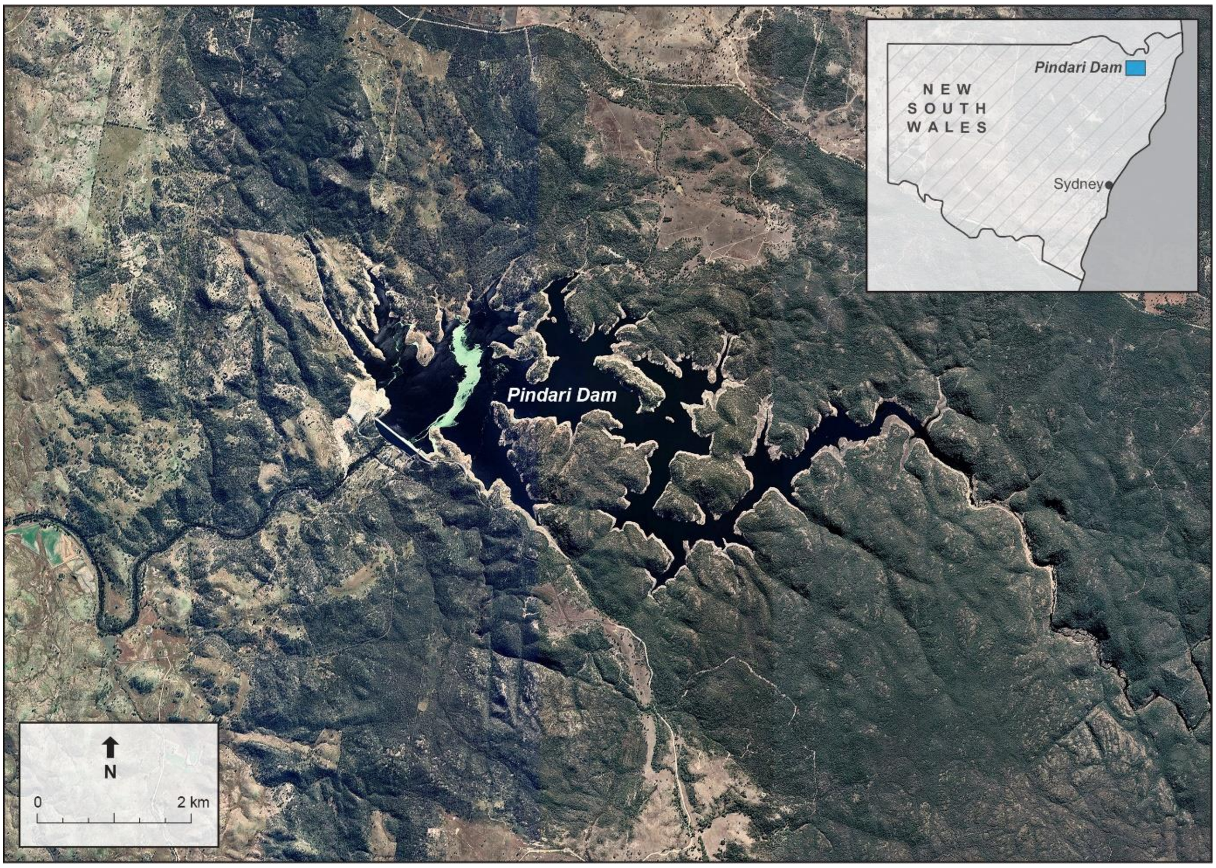

Figure 1 Pindari Dam location

3.3 Geometry and bathymetry

Table 1 summarises the quantitative information related to the geometry and bathymetry of Pindari Dam and reservoir.

Table 1 Pindari Dam and reservoir geometric and bathymetric information

Dam wall	
Spillway level (max. operating depth)	516 mAHD
Height	85 m
Length	954 m
Reservoir	
Maximum depth	73 m
Mean depth	29 m
Capacity	312,000 ML
Surface area	11 km^2
Catchment area	2,000 km^2

Figure 2 shows the stage-storage curve for Pindari reservoir (i.e. the relationship between water level and capacity).

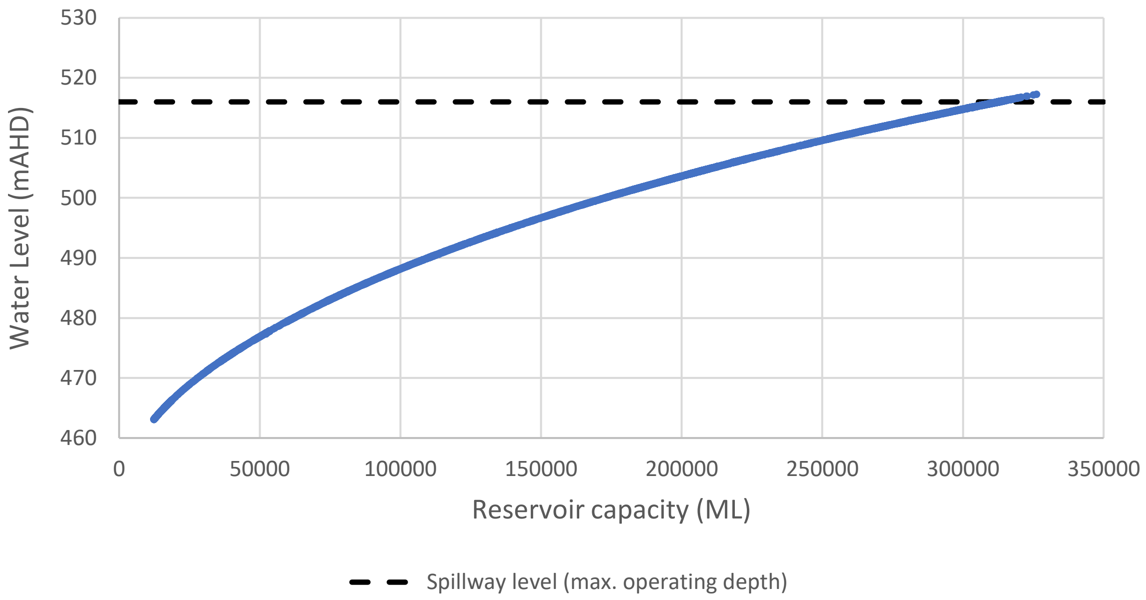

Figure 2 Stage-storage curve for Pindari reservoir

WaterNSW were unable to supply bathymetric surveys for Pindari reservoir at the time of writing this report. WRL received a 50 m resolution DEM of the Pindari reservoir bathymetry from Griffith University, which was used as an input for their numerical modelling trials (Figure 3).

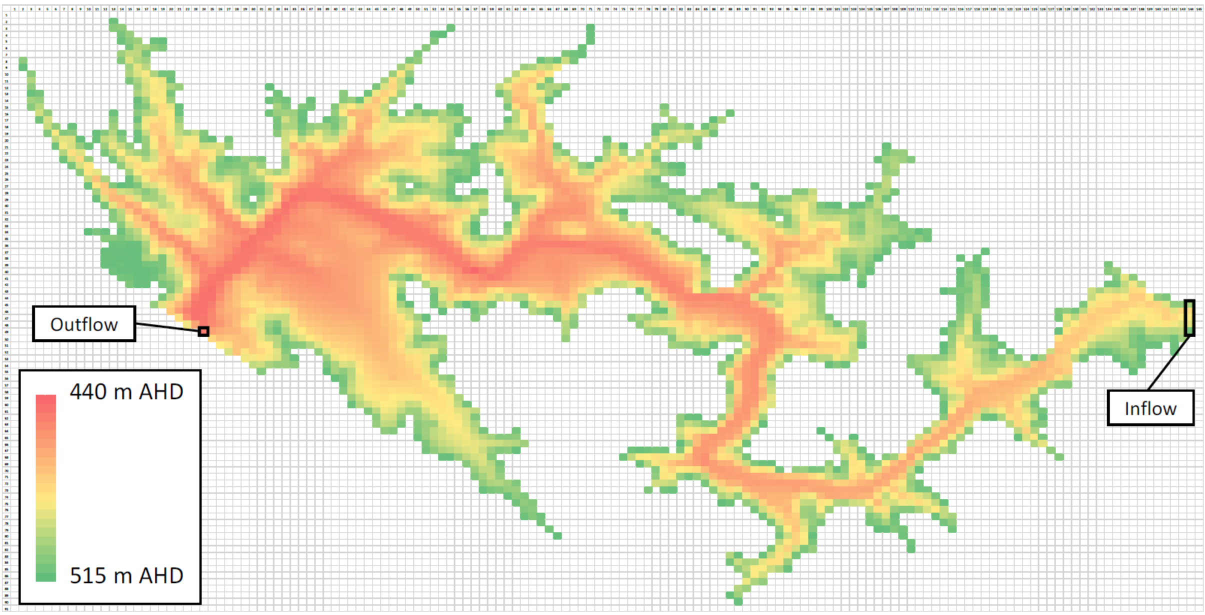

Figure 3 Pindari reservoir DEM, as prepared by Griffith University (Prentice *et al.*, 2021)

3.3.1 Reservoir shape

The DEM and aerial imagery of Pindari reservoir illustrate the irregular, winding shape of the main thalweg. These images show a number of branching sections deviating away from the main thalweg, which remain relatively deep up to the end of their respective channels.

The stage-storage curve and relatively deep mean depth (i.e. the capacity to surface area ratio) indicate the steep nature of the valley in which the reservoir has formed. In particular, the stage-storage curve is characterised by a relatively stable increase in reservoir capacity in relation to the water level, which highlights the steep gradient of the reservoir bathymetry. This sharp elevation gradient between the thalweg and edge of the reservoir is further demonstrated in the DEM, depicting changes in elevation of over 50 m over as little as 300 m horizontally.

The shape of a reservoir can have a significant impact on stratification and the potential effectiveness of strategies implemented to mitigate cold water pollution. The steep nature of Pindari's bathymetry will result in a smaller volume of warm water in the stratified surface layer, and a significant volume of cold water below the thermocline.

The deep nature of Pindari should theoretically benefit the blue-green algae suppression potential of bubble plume destratification, as the mixing depth should be such that algae is effectively light deprived. The branching sections of Pindari provide an opportunity to specifically monitor the effects of bubble plume destratification on shallower sections of a reservoir.

3.3.2 Offtakes

Pindari was originally constructed with a fixed intake tower with a low-level offtake (withdrawing from approximately 70 m below full supply level (FSL). As part of the dam enlargement in 1990, a new multi-level offtake was constructed with the capability to withdraw water from 12 different inlets (Preece, 2004). Appendix C provides detailed structural drawings of the offtake tower (Jonker *et al.*, 2020). Key details include:

- The top of the uppermost inlet sits at 516 mAHD (FSL)
- Inlets are 1.8 m (H) x 2.2 m (W)
- Inlets are equally spaced 3.15 m centre-to-centre
- An additional 5 m (diameter) inlet exists below the offtake tower inlets at 475.3 mAHD

(Preece, 2004) notes that, despite the cold water pollution mitigation capabilities of this new infrastructure, intakes were commonly set to withdraw from 6 to 15 m below the water surface to mitigate the potential downstream release of toxic cyanobacteria. Previously collected profile data between 1997 and 2001 (see Section 3.6.1) indicate that withdrawal at these depths would draw from below the thermocline, resulting in adverse cold water pollution to the downstream environment.

3.4 Inflows and outflows

Inflows and outflows from Pindari reservoir are available through WaterNSW's real-time water database (https://realtimedata.waternsw.com.au/). Gauges relevant to Pindari include:

- Severn Gauge at Strathbogie [416039] – records flows and temperatures upstream of Pindari Dam.
- Severn Gauge at Ducca Marri [416067] – records flows and temperatures downstream of Pindari Dam.
- Pindari Dam Gauge [416030] – records net inflow and release volumes at Pindari Dam.

Inflow and outflow data are a key component of the water balance of a reservoir system. In terms of investigating cold water pollution, downstream temperature data is especially important, as this can be indicative of the quantitative effects of mitigation strategies implemented in the reservoir. Outflow (downstream) data is key in analysing periods, magnitude and extent of cold water pollution. Significant drops in temperatures during warmer months represent instances of cold water pollution.

Figure 4 shows a time series of the upstream and downstream gauge temperatures between 2012 and 2022. This plot demonstrates instances where cold water pollution affected the downstream environment, highlighted by significant deviations in the up and downstream temperatures over summer. This may lend insight into the operational drawbacks of using the Pindari multi-level offtake to mitigate cold water pollution. Withdrawal depths might have changed from above to below the thermocline due to algae red alerts, initiating protocols to mitigate algae transport downstream and resulting in cold water pollution to the downstream environment. Typical examples of cold shock (discussed below) are highlighted in the figure.

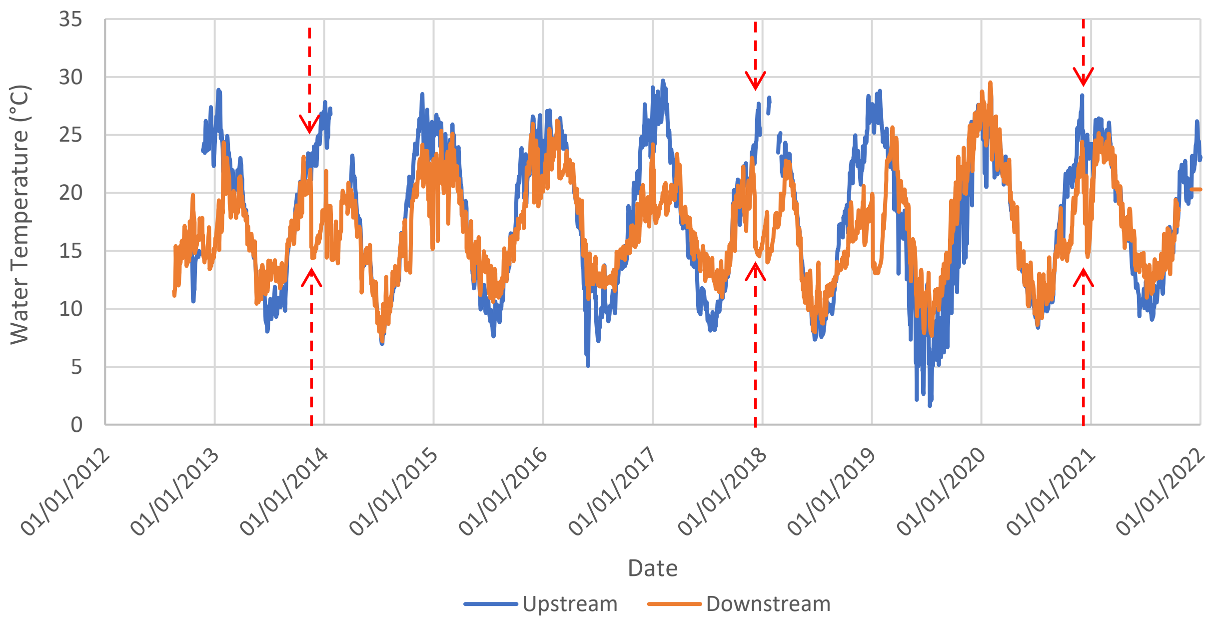

Figure 4 Measured temperatures upstream and downstream of Pindari (red arrows indicating typical instances of cold shock)

Peaks in the oscillating curves indicate summer periods, where water temperatures are at their maximum. Conversely, troughs indicate winter periods where water temperatures are at a minimum. Some observations in regards to the plot:

- Upstream temperatures are generally lower than downstream temperatures during the colder, winter periods. This is likely due to the large heatsink that the reservoir provides. Cooling mechanisms have a reduced effect, as the ratio of water volume to surface area (at which the cooling mechanisms occur) is far greater than the upstream river.

- In the summers of 2013, 2014, 2017, 2018, 2019 and 2021, distinct variability is observed between the upstream temperatures and downstream temperatures. This is indicative of selective withdrawal from below the thermocline resulting in cold water pollution to the downstream environment.
- In parts of the 2015, 2016, 2020 and 2021 summers, downstream and upstream temperatures are relatively well correlated. This may be indicative of selective withdrawal from above the thermocline, resulting in warmer waters being discharged downstream and mitigating cold water pollution. Alternatively, this may be related to dry periods where water levels and release volumes are considerably lower, minimising the effects of stratification and cold water pollution downstream.

Rapid drops from warm to cold downstream temperatures demonstrate instances of cold shock to the downstream river environment. Typical examples of cold shock occur around December 2013, December 2017 and December 2020 (highlighted by red, dashed indicators in Figure 4). Prior to these periods, both the up and downstream temperatures are observed to increase at a similar rate indicating effective cold water pollution mitigation through MLO operation. This is followed by a sudden drop in downstream temperature of up to 7°C over as little as 2 days, due to the release of water from below the thermocline. Cold shock can be ecologically detrimental, resulting in a high mortality rate in fish. This highlights one of the biggest disadvantages of managing cold water pollution through selective withdrawal.

Figure 5 and Figure 6 highlight some of the potential causes for cold water pollution and instances of cold shock downstream of Pindari.

Figure 5 shows release volumes, upstream and downstream temperature at Pindari. Prolonged release of large volumes of water coincide with summer periods (e.g. 2014, 2018 and 2019) where cold water pollution is observed to significantly affect downstream temperatures. Conversely, periods where release volumes are comparatively small coincide with summer periods (e.g. 2016 and 2020) where downstream temperatures remain relatively consistent with upstream temperatures. Instances of cold shock (i.e. sudden drops in temperature) coincide with the start of large volumetric releases (e.g. 2021 summer).

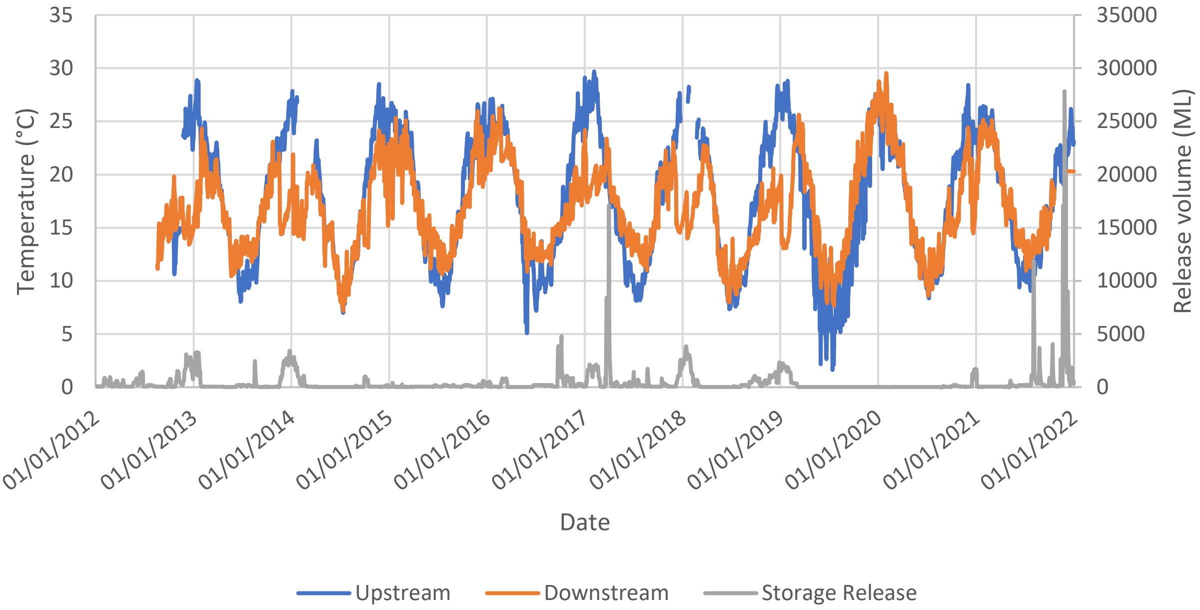

Figure 5 Measured temperatures upstream and downstream of Pindari with release volumes (measured at the dam)

Figure 6 shows reservoir water levels, upstream and downstream temperatures at Pindari. When the reservoir is full (i.e. the water level is at 516 mAHD, maximum operating capacity), water is released from the reservoir over the spillway. This inherently results in the release of warmer water from the surface of the reservoir which increases downstream temperatures. When the reservoir water level drops below the maximum operating capacity (i.e. below the top of the spillway), water is released through the offtake tower. If the offtake tower withdraws water from below the thermocline, this transition can result in instances of cold shock. A typical example of this occurs in December 2017 (Figure 7). While the reservoir is full, downstream temperatures are observed to increase at a rate similar to upstream. As the reservoir water level drops below 516 mAHD, the downstream temperature is immediately lowered. This suggests that water previously being released through spillway flows transition into release through the offtake tower through inlets below the thermocline.

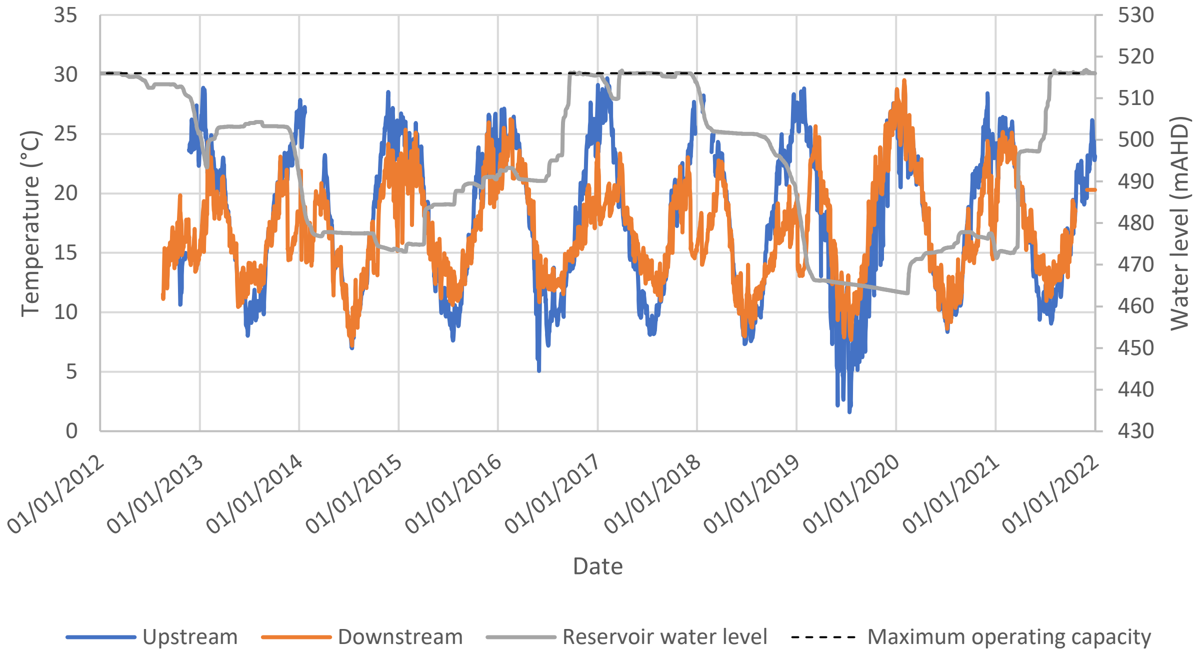

Figure 6 Measured temperatures upstream and downstream of Pindari with reservoir water levels

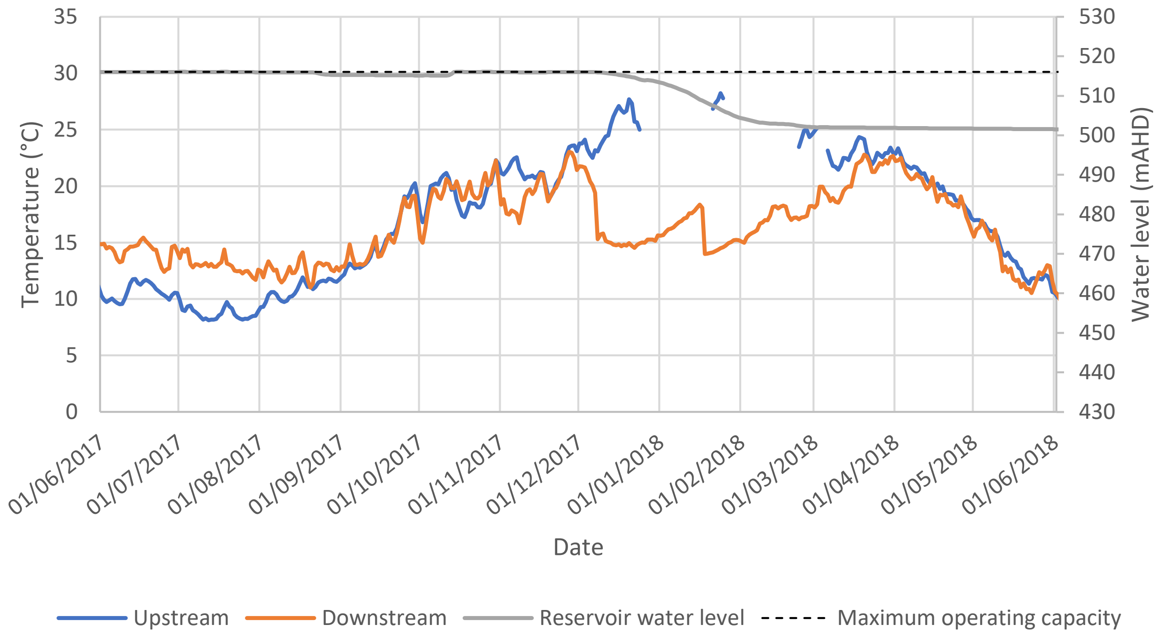

Figure 7 Measured temperatures upstream and downstream of Pindari with reservoir water levels (2017/2018 summer period)

It is important to note that upstream vs. downstream temperature is now regarded as unreliable as a standalone indicator of the magnitude of cold water pollution. A reservoir, by nature of being a significant volume of water and heat sink, invariably negates the ability for downstream temperatures to match upstream temperatures consistently.

3.5 Meteorological conditions

3.5.1 Nearby meteorological stations

Three nearby meteorological BOM stations were considered in assessing the meteorological conditions at Pindari Dam. These were selected based on an availability of the meteorological data considered as primary influencers of stratification and natural mixing, as well as their proximity to the site (Figure 8). These include:

- Pindari Dam station [054104]
- Inverell Research Centre station [056018]
- Glen Innes Airport AWS station [056243]

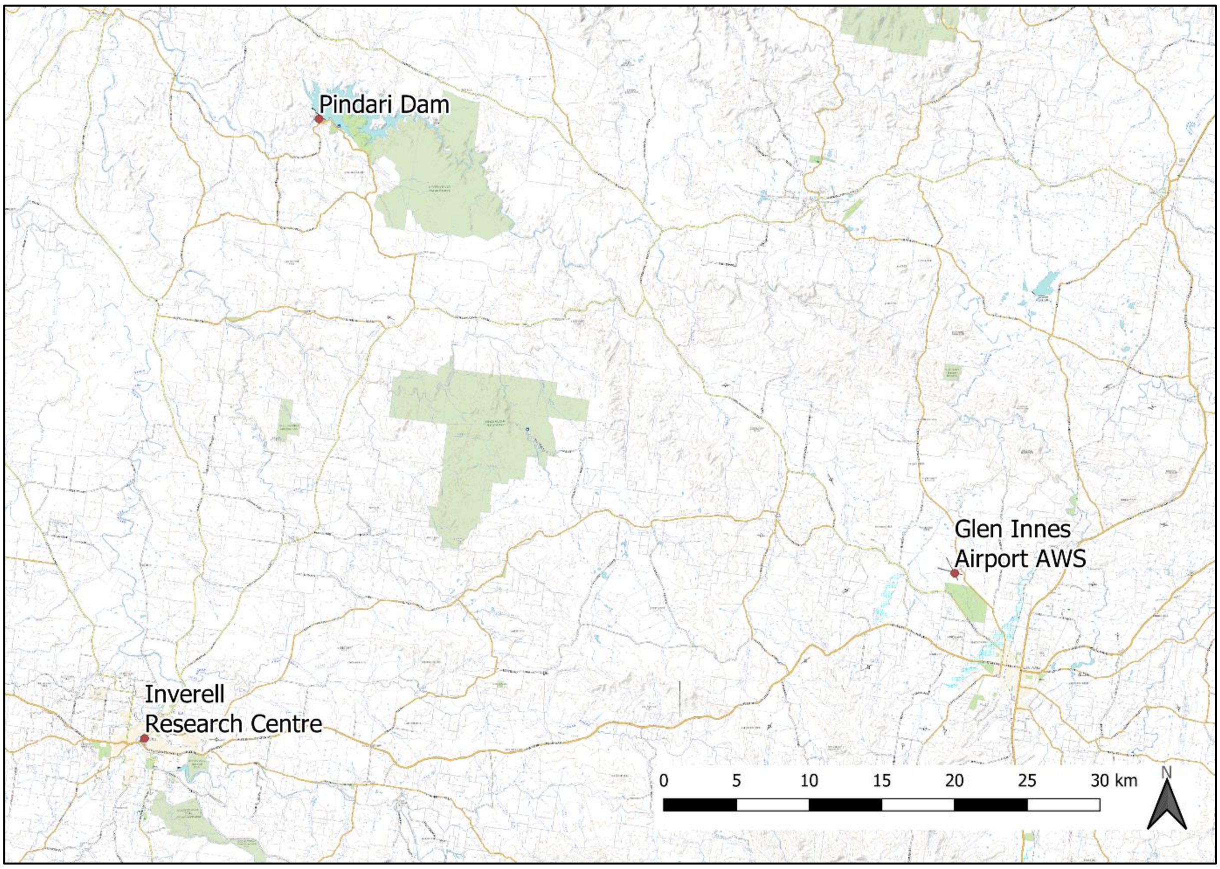

Figure 8 BOM station locations

The station at Pindari Dam provides data most representative of the meteorological conditions at the surface of the reservoir. Measurements were taken at a limited, daily (9 am) frequency up until late 2009, from which point recording frequencies were reduced further to 5 out of 7 days a week. This data is valuable for verification of data recorded at a higher and more consistent frequency from an alternative station.

Inverell Research Centre station is the closest (45.5 km) station to Pindari Dam with frequent and consistently available data. 3-hourly data (the highest frequency available for the respective data through the BOM) has been recorded from 2003 onwards. This data was used as meteorological inputs into the Griffith University modelling study and in terms of higher frequency data, is thought to best represent the meteorological conditions at Pindari. One of the more significant discrepancies between the two stations is the wind speed and directional data. This is likely due to the different topographical surroundings of each station.

Glen Innes Airport AWS station is the closest (54 km) automatic weather station (AWS) to Pindari Dam. The advantage of an AWS is its consistent, automatically recorded data sets. In comparison to Inverell Research Centre data, the data from the Glen Innes Airport AWS does not represent the conditions at Pindari as accurately. This may, in part, be attributed to the ~600 m variation in elevation between the Pindari and Glen Innes Airport stations (where Inverell to Pindari elevations only vary by ~200 m). Data from this station will be valuable for filling gaps that might exist in the more reliable Inverell Research Centre data, however will not likely be used to directly assess conditions at Pindari.

Table 2 summarises the frequency of recording and periods over which data is available at each of the stations. Assessments made in this report consider data collected from 1997 onwards, as in-reservoir depth profile temperature data is only available between 1997 – 2001 (discussed further in 3.6.1).

Table 2 Period and frequency of recording meteorological conditions at BOM stations

	Pindari Dam		**Inverell Research Centre**		**Glen Innes Airport AWS**	
Meteorological parameter	Period	Frequency	Period	Frequency	Period	Frequency
Air temperature (instantaneous)	01/08/1971 – 17/09/2009	Daily (9am)	01/01/1965 – 06/12/2002	Daily (9am)	22/10/1996 – current	3-hourly
	17/09/2009 – current	5/7 days per. Week (9am)	17/12/2002 – current	3-hourly		
Wind speed and direction (averaged over a 10-minute period)	01/08/1971 – 17/09/2009	Daily (9am)	01/01/1965 – 06/12/2002	Daily (9am)	22/10/1996 – current	3-hourly
	17/09/2009 – current	5/7 days per. Week (9am)	17/12/2002 – current	3-hourly		
Relative humidity (instantaneous)	01/08/1971 – 17/09/2009	Daily (9am)	01/01/1965 – 31/12/1966 01/08/1970 – 06/12/2002	Daily (9am)	22/10/1996 – current	3-hourly
	17/09/2009 – current	5/7 days per. Week (9am)	17/12/2002 – current	3-hourly		
Solar radiation (total)	01/01/1990 – current	Daily	01/01/1990 – current	Daily	01/01/1990 – current	Daily
Atmospheric pressure (instantaneous)	N/A	N/A	17/12/2002 – current	3-hourly	22/10/1996 – current	3-hourly
Rainfall (total)	01/08/1971 – current	Daily	01/05/1949 – current	Daily	22/10/1996 – current	Daily
Cloud coverage (instantaneous)	01/08/1971 – 17/09/2009	Daily (9am)	01/01/1965 – current	Daily (9 am)	19/05/2015 – current	3-hourly
	17/09/2009 – current	5/7 days per. Week (9am)				

3.5.2 Measured Parameters

Wind speed and direction

Wind speed and direction affects the mixing processes that occur at the surface of the reservoir. These processes will have minimal effect on the reservoir below the thermocline during warmer months, where meteorological conditions that induce stratification dominate the thermodynamic state of the reservoir.

Wind speed and direction varies at a much higher temporal frequency (minutes) than in-reservoir stratification and mixing processes (daily to biannually). Given this temporal variation, detailed numerical modelling can assist with quantitatively relating changes in wind speed and direction to mixing mechanisms within a reservoir system.

Inverell Research Centre station wind speed and direction is considered the current best frequently available representation of the conditions at Pindari Dam. Data from this station was used for the preliminary AEM3D modelling undertaken as part of this report.

Air temperature

Air temperature plays a role in the heat budget at the surface of the reservoir. Increased air temperatures increase the water temperature at the surface of the reservoir, instigating and maintaining stratification through the warmer months of the year. Conversely, lower air temperatures can induce evaporative cooling at the surface of the reservoir, affecting both diurnal and seasonal natural mixing.

Air temperatures can be an important qualitative and quantitative trigger for the initiation of stratification in a reservoir. For detailed analysis, air temperatures cannot be considered an isolated metric which controls the onset of stratification, as this process is complicated and relies on a number of meteorological and hydrological conditions. However, simple analysis of historical air and reservoir profile temperature data can provide insight into the general timing of the onset of stratification for a particular reservoir.

Figure 9 and Figure 10 demonstrates the value of air temperatures in assessing the timing of the onset of stratification. Both plots show the temperature gradient within Pindari reservoir (i.e. the difference between the surface and bed temperature) and the 7-day rolling average of the maximum daily air temperature recorded (at the Pindari BOM station) over the 1997/98 and 2000/01 summers. Stratification initiates at two different times over these periods, however both coincide with the maximum temperature rolling average increasing to ~ 20°C. On a preliminary basis, this may represent the threshold at which cold water pollution mitigation measures might be commenced. It is noted that reservoir temperature gradient can exceed 12°C when air temperatures are maintained above 30°C.

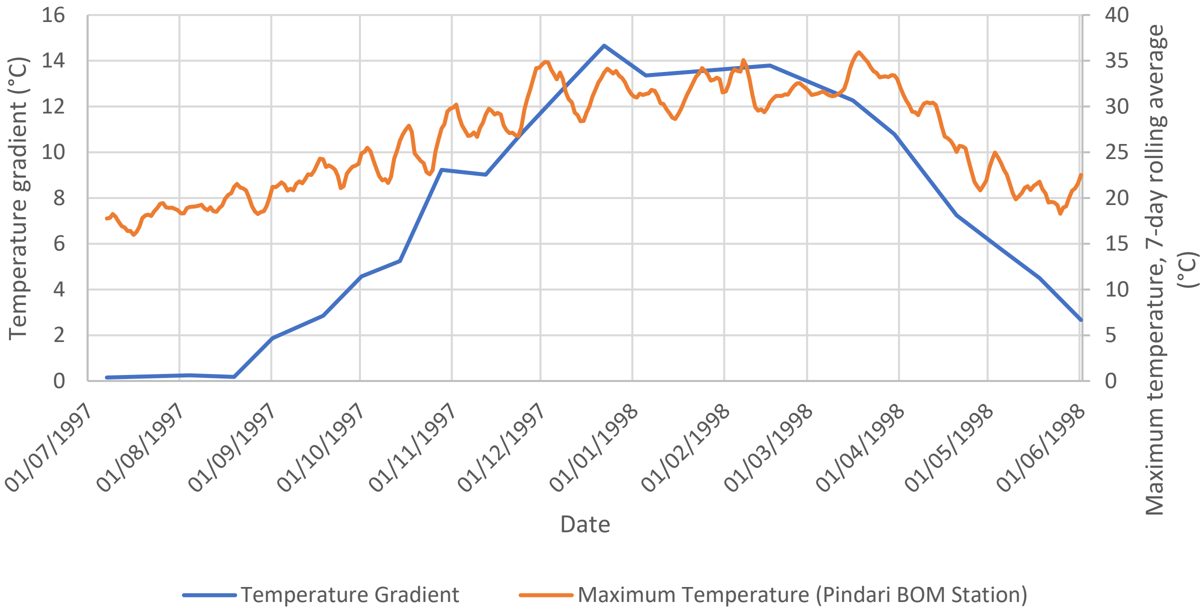

Figure 9 Reservoir temperature gradient and maximum air temperature 7-day rolling average for 1997/98 summer period at Pindari Dam

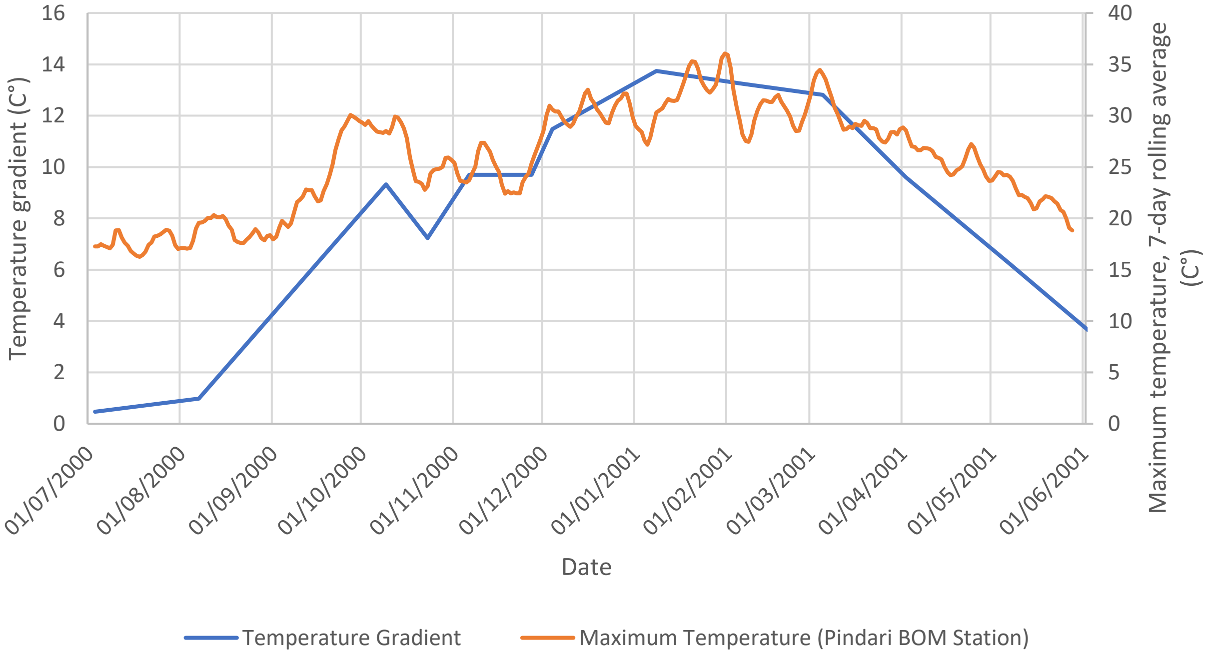

Figure 10 Reservoir temperature gradient and maximum air temperature 7-day rolling average for 2000/01 summer period at Pindari Dam

At a smaller time scale, it is important that air temperatures are well represented to capture the diurnal variations in heating and cooling in the reservoir surface layers. Increasing and decreasing temperatures over the day and night cycle can impact both the short-term stratification and mixing processes in a reservoir. These short-term variations may be considered in optimisation of cold water pollution mitigation strategies in detailed design (e.g. intermittent operation of a bubble plume destratification system to minimise energy costs).

While there is some variation between the temperatures recorded at the Inverell Research Centre and Pindari BOM stations, they are unlikely to significantly impact assessment of stratification or mitigation strategies at this preliminary stage of investigation. For consistency, air temperatures used for assessment and modelling in this report were taken from the Inverell Research Centre meteorological records.

Solar radiation

In isolation, solar radiation is likely to have the biggest impact on stratification in the reservoir. Short wave radiation penetrates past the water surface and through the water column, decaying as depth increases. This results in significant energy input into the reservoir, which results in heating and the development stratification.

Solar radiation follows a similar biannual pattern to air temperatures, peaking in summer and reaching a minimum through winter (Figure 11). As with air temperatures, solar radiation may be useful as a quantitative trigger for the initiation of cold water pollution mitigation measures based on analytically derived thresholds.

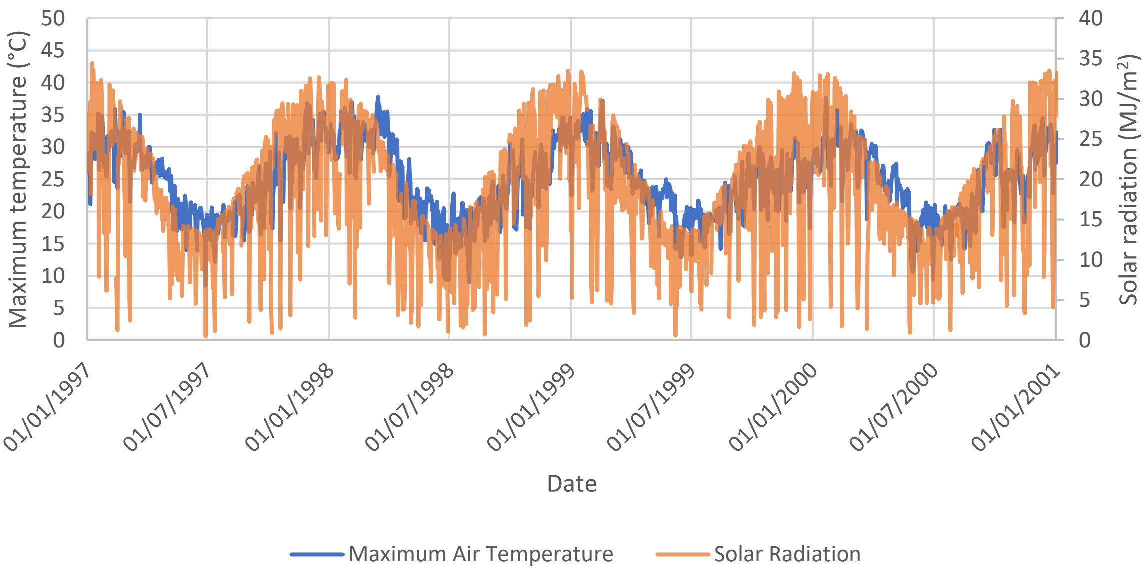

Figure 11 Maximum air temperature and solar radiation trends at Pindari Dam (1997 – 2001)

Solar radiation (measured as total daily global exposure) is provided consistently at all BOM stations. This data is satellite derived, and based theoretically on the location of the station. Given the proximity of Inverell to Pindari, there should be minimal discrepancy between the two sites. Variations may occur in instances of varying cloud coverage which are seemingly accounted for in the solar radiation data provided by the BOM. Figure 12 demonstrates that, as cloud cover decreases, solar radiation increases (and vice versa).

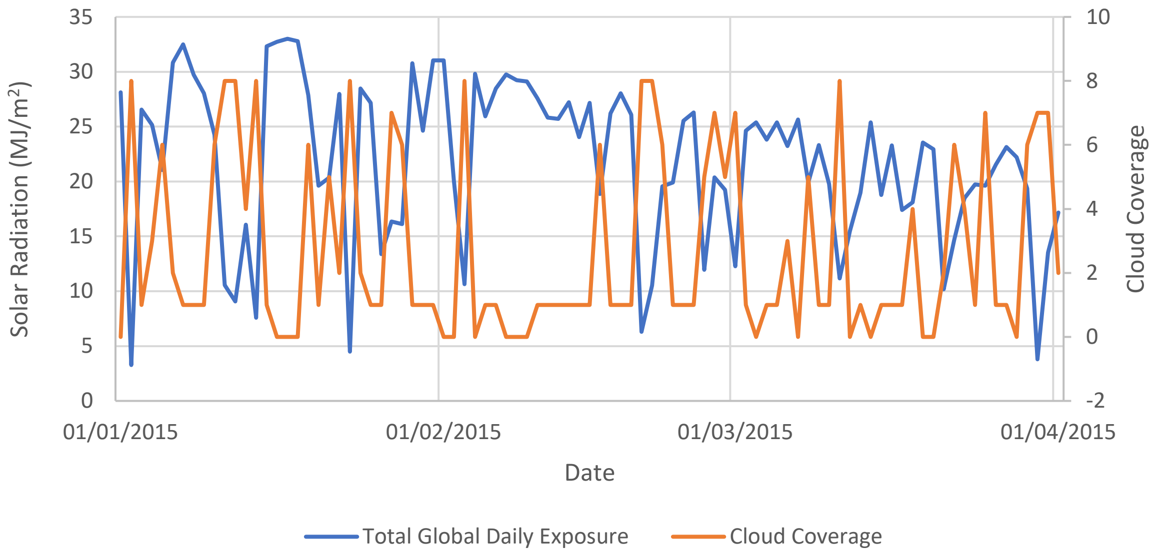

Figure 12 Plot demonstrating the relationship between BOM solar radiation and cloud coverage measurements

Cloud cover

Cloud cover affects the total energy that reaches the surface of a reservoir through solar radiation. BOM provides this data as an okta measurement, a value from 0 to 8 representing the percentage of cloud cover recorded (e.g. 0 = 0%, 4 = 50%, 8 = 100%). As cloud cover increases, solar radiation reaching the surface of the reservoir is reduced (as identified previously).

Cloud cover data used in analysis and modelling undertaken as part of this report was taken from the Inverell Research Centre BOM station.

Rainfall

Rainfall has a minimal effect on stratification and mixing, compared to other meteorological inputs into the reservoir system. More so, rainfall contributes to the water balance of the reservoir. Rainfall data has limited use in the quantitative assessment of stratification, however, it may be useful for the qualitative assessment of blue-green algae bloom events. Large rainfall events result in significant runoff, which can introduce a significant nutrient load to a reservoir system. This can feed and increase algae growth, causing the aforementioned blue-green algae blooms. Analysis of the effects of rainfall on algae growth was not undertaken as part of this study, due to an unavailability of necessary data.

Relative humidity and atmospheric pressure

Relatively humidity simply represents the percentage of water vapor in the air compared to the maximum possible, at a given temperature. Relative humidity affects the potential for evaporation at the surface of the reservoir, and thus evaporative cooling. As relative humidity increases, evaporation decreases. This, and atmospheric pressure, are relatively unimportant for qualitative assessment of the meteorological conditions at Pindari; rather, they are a necessary input to the AEM3D model.

The sensitivity of the model to variations in this data is unknown, however discrepancies between the Inverell and Pindari data are likely insignificant considering the calibration data available.

Inverell Research Centre BOM station data was used for both relative humidity and atmospheric pressure inputs in AEM3D as part of the preliminary assessments undertake in this report.

3.6 Reservoir water quality and temperature measurements

3.6.1 Temperature profiling

Temperature profile data was collected in Pindari Dam between 1997 and 2001. Data was received labelled as “Station 1 Profiles”. A recent report (NSW Department of Planning Industry and Environment, 2020) details current and historical monitoring at Pindari Dam and refers to the dam wall sampling location as “Station 1”. Based on the depths of the temperature profiles obtained, it is assumed that these were collected at the dam wall.

Detailed numerical analysis of the meteorological effects on the stratification recorded between 1997 and 2001 is limited as BOM data from the same period was inconsistently recorded and only available at a maximum of daily recording frequency. This consequently makes it difficult to calibrate and verify the AEM3D model using this profile data, given the uncertainty surrounding the meteorological model inputs. The Griffith University modelling study demonstrated that these profiles could be used to adjust modelling parameters to ensure the thermocline depth was more accurately modelled.

Plots of the profiling data (Figure 13) demonstrate how Pindari periodically stratifies over a number of consecutive summers.

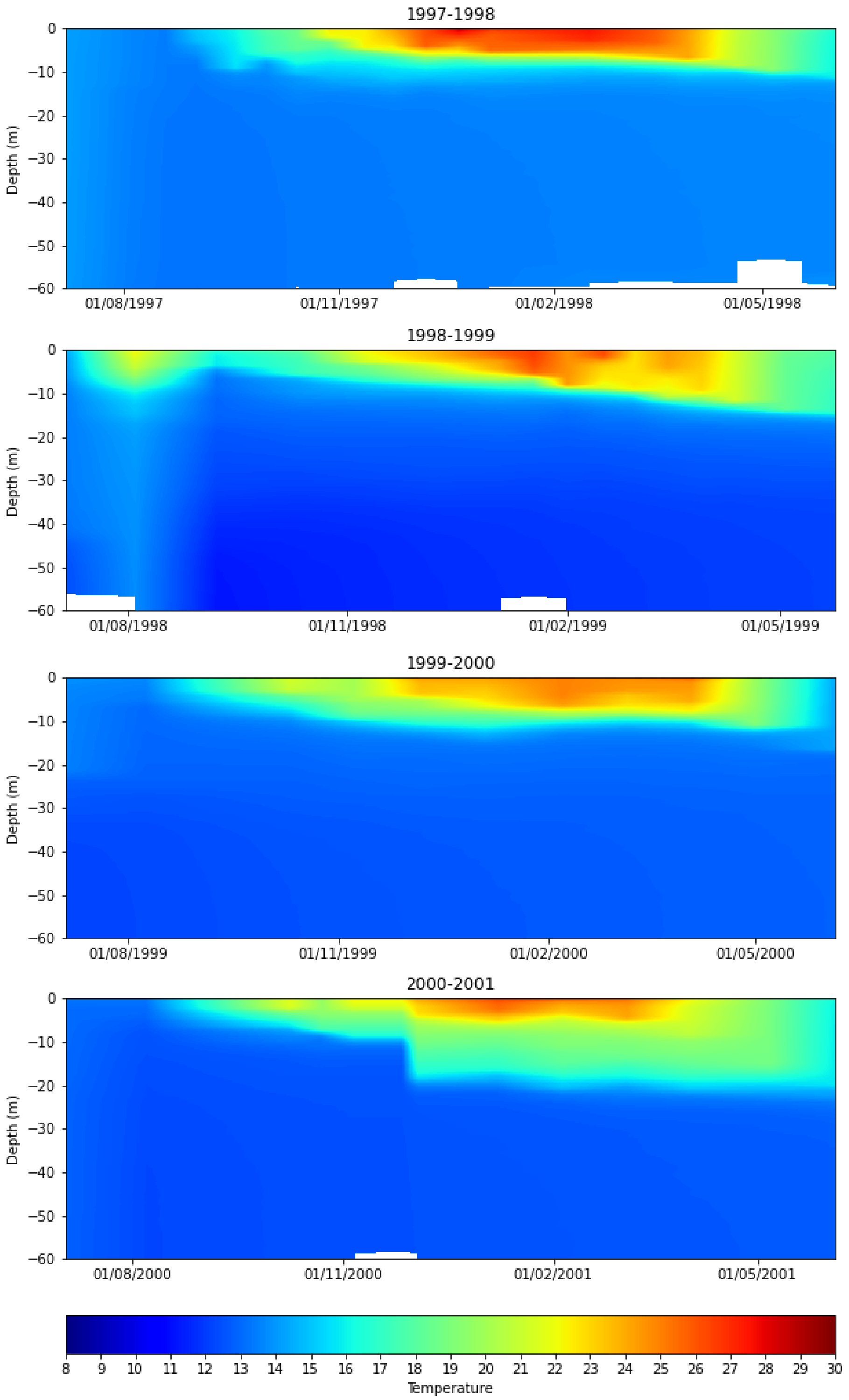

Figure 13 Profile temperature data from 1997 to 2001 demonstrating stratification in Pindari reservoir

3.6.2 Long term water quality monitoring

Historically, minimal long-term water quality monitoring has been undertaken for Pindari Dam. In the reservoir itself, water quality monitoring is limited to blue-green algae measurements at three recreationally used locations (discussed further in 3.6.3). A routine water quality monitoring station upstream of Pindari (at Strathbogie Bridge) collects monthly inflow samples to check total nitrogen, phosphorus, turbidity, dissolved oxygen and pH.

This limited data availability, especially at the temporal intervals at which it is collected, is minimally useful moving forward. Understanding the effects of stratification and mitigation strategies on water quality for Pindari Dam will, at minimum, require a long-term monitoring program collecting data from within and downstream of the reservoir. Upstream monitoring assists with a greater understanding of causes for declines in water quality within the reservoir. Data should be collected at least daily, to understand the short-term changes to water quality effected by short-term changes to stratification or mitigation strategy operations (e.g. initiating a destratification system).

3.6.3 Algae observations

Blue-green algae monitoring at Pindari Dam involves routine sampling from three locations around the reservoir: dam wall, boat ramp and the upstream inflow. Blue-green algae biovolume data collected from these locations is used to assign alerts based on National Health and Medical Research Council guidelines (NHMRC, 2008). Table 3 summarises alert thresholds, triggered by one of three measured parameters:

- Trigger 1 – *Microcystis aeruginosa* concentration, in cells/ML
- Trigger 2 – Biovolume, where toxin-producing cyanobacteria are dominant (> 75%), in mm^3/L
- Trigger 3 – Biovolume, where toxin-producing cyanobacteria are not dominant (< 75%), in mm^3/L

Table 3 Blue-green algae alert thresholds

Alert	Trigger 1 (cells/ML)	Trigger 2 (mm^3/L)	Trigger 3 (mm^3/L)
Red	> 50,000	> 4	> 10
Amber	5,000 – 50,000	0.4 – 4	0.4 – 10
Green	< 5,000	< 0.4	< 0.4

Historical records of blue-green algae biovolume or concentration data are currently unavailable to WRL. Figure 14 was adapted from a recent report, and shows a record of these biovolumes as sampled at Pindari Dam wall between 2007 and 2013. The horizontal red line indicates the red alert threshold of 4 mm^3/L (for trigger 2). Red alerts are triggered roughly 20 – 30% of the time through the 5-year period shown. More importantly, there appears to be at least one period in each summer where the red alert threshold is triggered. These events would have triggered algae release mitigation protocols for the MLO at Pindari, likely resulting in cold water pollution downstream and instances of cold shock.

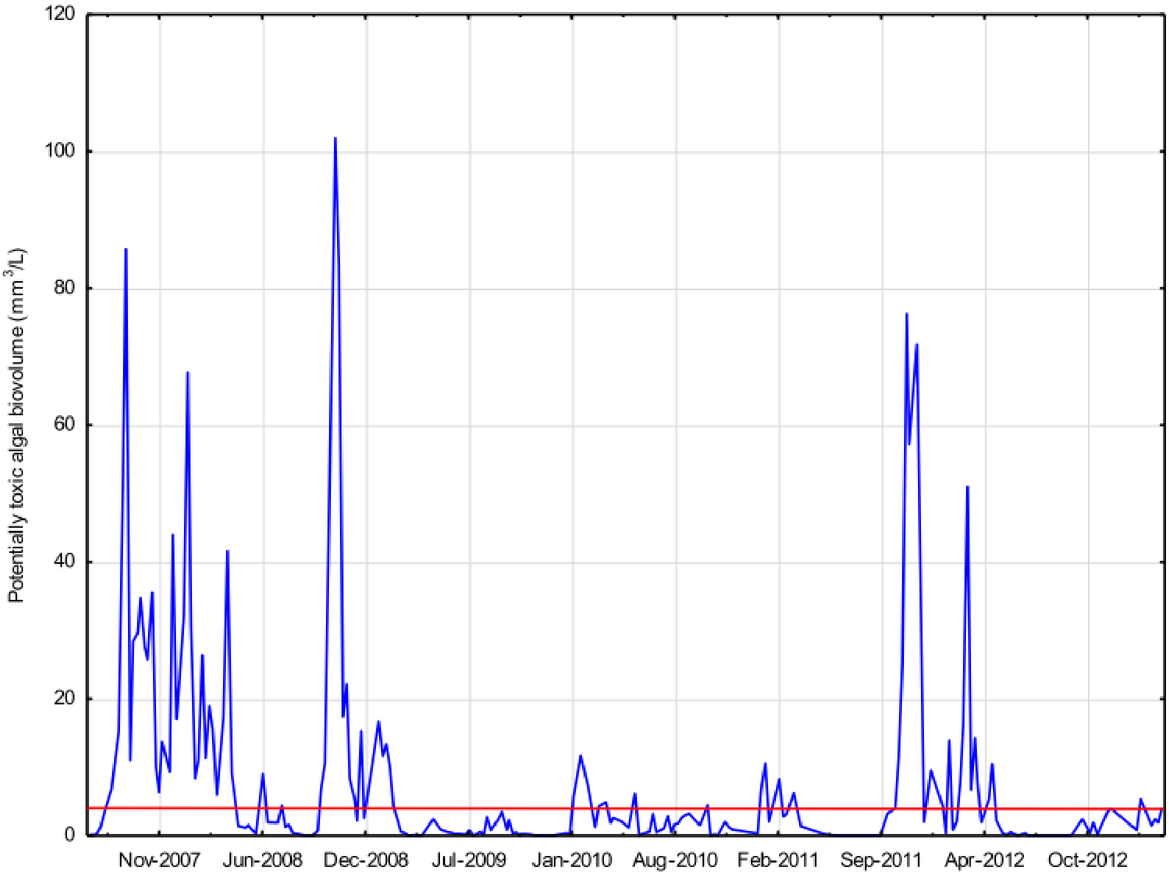

Figure 14 Potentially toxic algae biovolumes at Pindari Dam (NSW Department of Planning Industry and Environment, 2020)

Upstream and downstream temperature records are unavailable for most of the period shown in the above figure, with the exception of the 2012/2013 summer (Figure 15). This is too small a sample of data from which to draw definitive conclusions, however it does demonstrate the deviation in upstream and downstream river temperatures around the time that algae biovolume exceeds the red alert threshold. This would have triggered the selective withdrawal operational protocols, dropping the withdrawal depth to below the thermocline to mitigate the release of the potentially toxic algae downstream, at the expense of introducing cold water pollution.

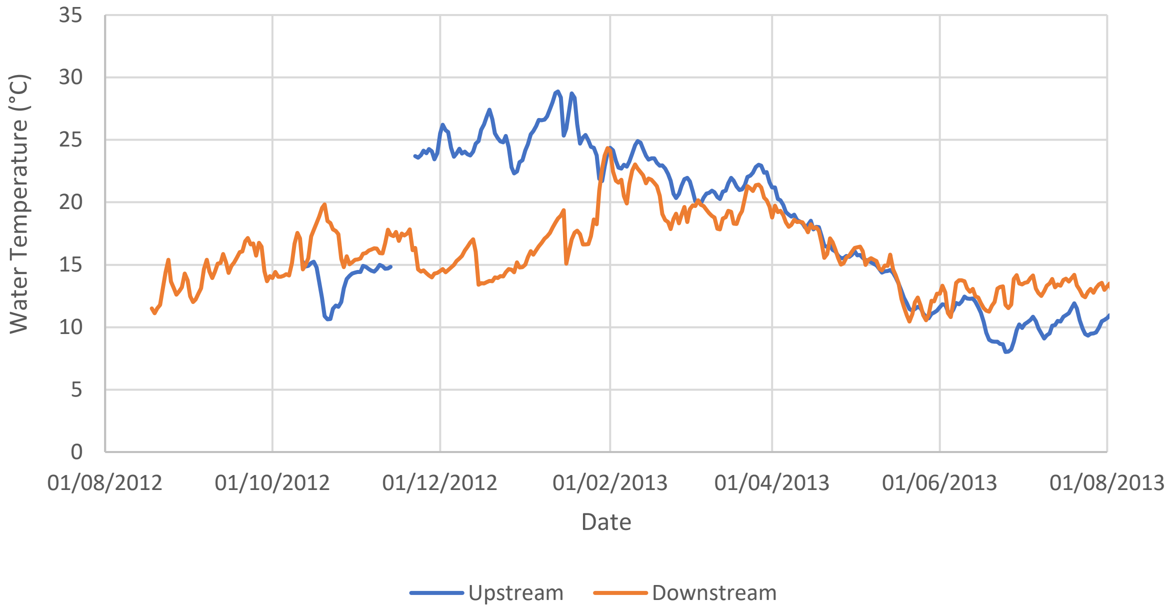

Figure 15 River temperatures upstream and downstream of Pindari Dam over the 2012/2013 summer

More recent records of the algae biovolume measurements could be used to verify the effect conflicting operating protocols for cold water pollution mitigation and algae transport mitigation have on instances of cold water pollution at Pindari reservoir.

3.7 Water Release Strategies

Pindari Dam currently uses water release strategies aimed at both maintaining environmental flows and mitigating cold water pollution.

3.7.1 Environmental flows

Table 4 summarises the rules applied to water releases at Pindari Dam with the aim of maintaining environmental flows (NSW Department of Planning Industry and Environment, 2020):

Table 4 Environmental flow rules for Pindari Dam water release

Flow rule	Flow/Volume Arrangements	Benefits
Continuous low flow rule	10 ML/day (minimum)	• Riparian flow and connectivity of downstream pools and riffles
Translucency rule	Release of specified inflows into Pindari Dam • Up to 50 ML/day September – May • Up to 200 ML/day June – August	• Provide natural flows downstream to the next point of significant inflow • Consistent, deliverable and auditable arrangement
Stimulus flow rule	4,000 ML/year set aside and released between 1 August and 1 December, triggered by inflow into Pindari Dam greater than 1,200 ML/day in the four months preceding	• A flow in the river that mirrors a naturally occurring hydrograph • Add benefit to translucency environmental health releases • Targeted pre-season cues to fish breeding • Regularly wet and inundate interconnected riparian areas • Opportunity for more extensive stimulus flows in the system which will extend aquatic benefits further downstream
Plan extraction limits	Limit on long-term average volume of water that can be extracted. Reserve flows (approximately 60% of average annual flow) for environmental health maintenance	• Slow the decline in water quality by preventing pools from stratifying and stagnating

3.7.2 Cold water pollution mitigation

As part of Stage One and Two of the NSW Cold Water Pollution Strategy, improved operating protocols for dams with existing multi-level offtakes were designed and implemented to mitigate cold water pollution. Specific operational protocols for Pindari reservoir are not available currently, however the WaterNSW Cold Water Pollution Operating Protocols stipulate general rules that are applied to dams with existing selective withdrawal capabilities.

Figure 16 shows a flow chart of generic procedures outlining this strategy. Note that the specific quantitative measures and operational procedures may not directly relate to Pindari.

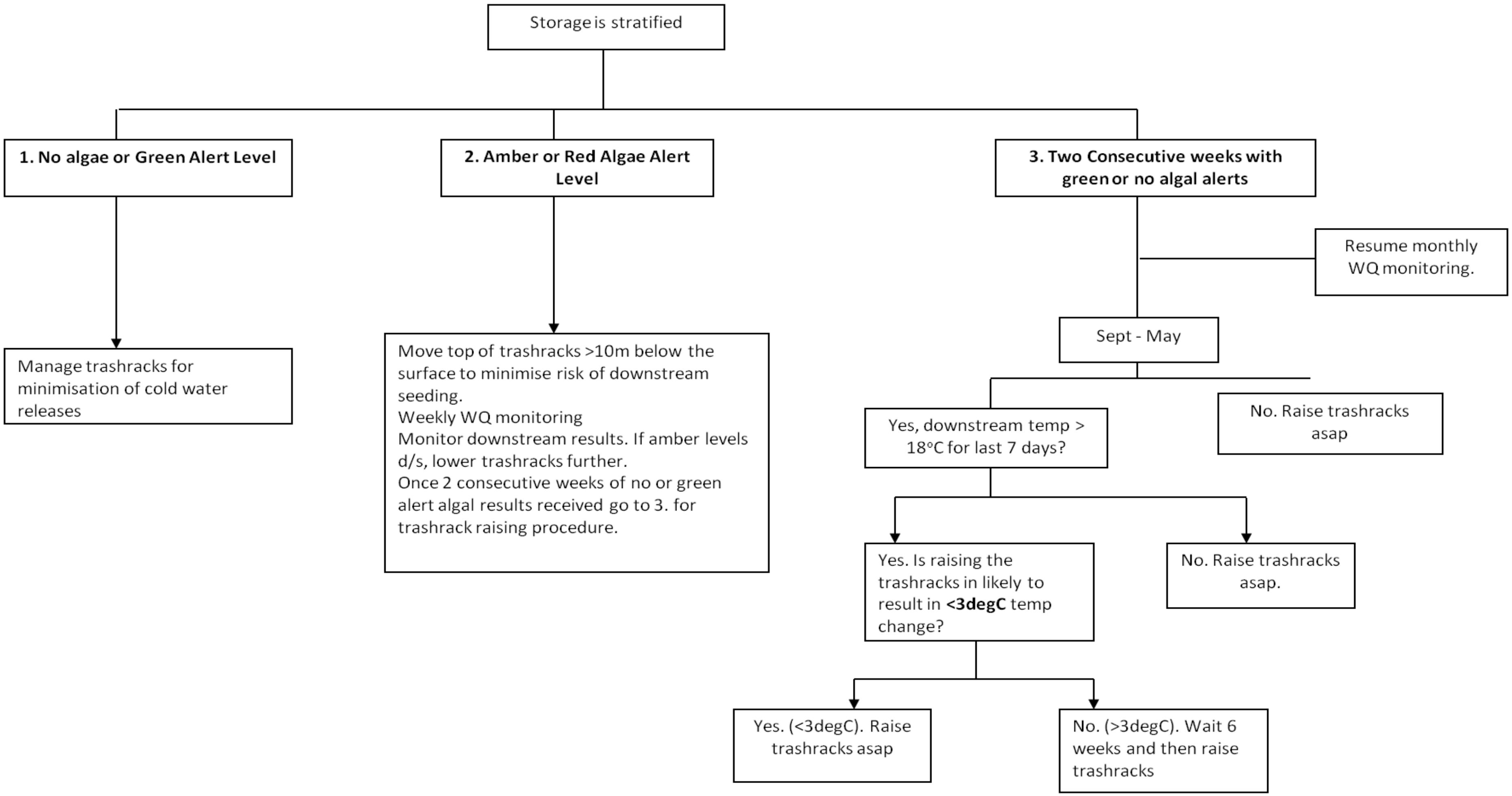

Figure 16 Generic operational procedures for mitigating cold water pollution using a multi-level offtake structure (Hardwick *et al.*, 2011)

In essence, the strategy aims to withdraw water from the upper-most inlet (5 to 8 m below the surface) in the water column, to ensure warm surface water is released downstream. In the event of an algae red alert (see Section 3.6.3), withdrawal can be lowered to as deep as 12 m below the water surface. Withdrawal at this depth would likely draw water from close to or below the thermocline, resulting in cold water pollution. This is a significant consideration for the operation limitations of using a multi-level offtake to mitigate cold water pollution.

Flow through each inlet is controlled by a series of cover plates and trash racks (see Appendix C). Cover plates limit flow through inlets; trash racks allow flow through inlets while simultaneously limiting flowthrough of larger objects which may cause blockages.

3.8 Data gaps and recommendations for further data collection

As discussed as part of several data-related sections of this report, there are a number of gaps in the currently available data surrounding the bathymetric, structural, hydrological, meteorological and water quality conditions and information at Pindari Dam. These gaps exist either due to:

- Inconsistencies or gaps in the current monitoring network and regime upstream of, downstream of and in Pindari Dam.
- A current lack of access or knowledge of already existing data.

3.8.1 Data that most likely exists but which we don't have

Bathymetric and structural information

The only known bathymetric information available to WRL currently are the DEM's provided by Griffith University. This is valuable information, however detailed bathymetric surveys will be beneficial for future detailed design of a pilot bubble plume destratification system for Pindari Dam. It is understood that this is information WaterNSW might already have. Should this data be outdated, it would be prudent to undertake an up-to-date survey of the reservoir.

Structural information would assist in understanding the location and limitations of the current dam and offtake structure for the purposes of designing a destratification system (e.g. could diffuser or distribution pipelines be anchored to the dam wall for easier maintenance access). WRL currently has access to as-constructed drawings of the existing offtake tower (Appendix C) but not those of the dam wall.

If available, a request should be made for:

- Detailed bathymetric surveys of Pindari reservoir
- As constructed drawings of Pindari Dam

Algae monitoring data

WaterNSW routinely samples water from three different locations in Pindari Dam for potentially toxic algae biovolume and concentrations. This data, as previously discussed, may benefit a qualitative understanding of the issues caused by conflicting cold water pollution and downstream algae transport mitigation protocols given the currently operating multi-level offtake in Pindari Dam. As well as this, this data may provide insight into the causes of algae blooms, and potential predictability of these events which are considered a major limitation to cold water pollution mitigation strategies.

If available, a request should be made for:

- Blue-green algae monitoring data
- Records of historical algae red-alert triggers

3.8.2 Data that should be collected

In-reservoir monitoring

In-reservoir data is among the most important in terms of accurately assessing the state of stratification in a reservoir. Historical data of this nature is key to developing a holistic understanding of the stratification and mixing processes with Pindari Dam. By understanding these processes, and how they may affect water quality in and downstream of the dam, mitigation strategies can be more effectively designed. A lack of this data limits the ability to potentially optimise the mitigation strategy employed, and therefore limits the ability to reduce costs.

In general, in-reservoir data is most effective as a depth profile. A number of parameters can be captured in depth profiling, giving an insight into the thermal stratification structure within the reservoir and associated changes to water quality. The parameters that are necessary to monitor include:

- Temperature – essential to understanding the thermal structure of the reservoir water column and stratification as it develops and changes with artificial destratification or varying meteorological conditions. For a pilot destratification system with variable flow rates, observing the changes to the thermal structure in the water column over short periods due to varied flow rates will be crucial for optimisation.
- Cyanobacteria (blue-green algae) concentration/biovolume – currently the biggest non-monetary challenge for mitigating cold water pollution. Understanding how bubble plume destratification may effect and potentially limit toxic cyanobacteria is crucial to its success as a strategy.
- Dissolved oxygen (DO) – a secondary, key indicator of stratification in a reservoir. DO concentrations are distributed through the water column similarly to temperatures in a stratified environment, with a sharp gradient at the thermocline. As well as this, DO is a key component of a healthy aquatic environment, and thus a key indicator of water quality in a reservoir system.

While not necessary, a number of other parameters can be monitored to further increase the understanding of the benefits of artificial destratification in a reservoir system, including:

- Soluble metals (iron and manganese) – considered to negatively impact water quality, from both an environmental and human-health perspectives. The concentrations of these are generally linked to DO concentrations, as they are released at the sediment-water interface at the bed of the reservoir under anoxic (low DO) conditions. Increasing DO throughout the water column is likely to decrease concentrations, however it might be beneficial to understand the rate at which this occurs and if there are limitations to mitigation strategies in deep reservoirs such as Pindari.
- Nutrients (phosphorus and nitrogen) – contribute to the growth of algae, and therefore can impact water quality by increasing cyanobacteria biovolume/concentration. These nutrients are generally released under the same anoxic conditions as soluble iron and manganese.

Additionally, these nutrients can enter the reservoir through rainfall runoff events. While not necessary to understanding the direct effects of artificial destratification for mitigating cold water pollution, it may provide a greater insight into the nutrient cycle within the reservoir system and potential predictability of algae blooms.

- Redox (oxidation reduction potential) – relates to the potential for both soluble metals and nutrients to be released at the bed of the reservoir.
- pH – often considered a valuable metric for understanding water quality. Specific benefits in regards to monitoring the effects of destratification are yet to be explored as part of this study, however previous literature suggests lowered pH may facilitate a shift away from blue-green algae dominance (Chaaya and Miller, 2022). Monitoring pH would likely incur minimal additional costs.

At a minimum, this data should be collected daily (ideally midday to early afternoon to realise effects at peak stratification) and in the vicinity of the offtake tower to understand the diurnal variations of the system and potential downstream effects. Anything longer than this might ignore key transitions between states of stratification or water quality in the reservoir affected by the operation of a destratification system and constant or natural variations to meteorological and hydrological conditions.

Ideally, automatic and on-going telemetered profiling infrastructure would be used to continuously collect data from a selected few (two at a minimum) locations around the reservoir. The key benefits of a state-of-the-art monitoring system include:

- Providing an intrinsic and detailed understanding of the effects of bubble plume destratification on all the aforementioned parameters at small time-steps.
- Understanding the varying effects an operational destratification system would have on different parts of the reservoir (e.g. deeper section vs. shallow section, close to the diffuser line vs. in a shall branching creek).
- Providing a key calibration and input datasets for detailed numerical modelling of the reservoir. A greater degree of accuracy for model inputs representing measured parameters ensures the model is more likely to produce more accurate results. A lack of historical data severely reduces the accuracy to which a model can represent a real system, due to a lack of calibration.
- The ability to vary flow rates and operating intervals of a pilot destratification system to gauge the response of the water quality and thermal parameters measured. This will be of particular importance for blue-green algae, as bubble plume destratification should theoretically reduce the overall growth of dominant, toxic algae in the system. If it does not, profiling will indicate whether artificially mixing the reservoir will result in an increase in concentrations near a withdrawal inlet by mixing it from the surface to a deeper part of the water column.
- Providing a key feedback loop for an optimised and automated destratification system. While in it's infancy, the idea of an optimised system would be to regulate the flowrate at the compressor based on the current thermal regime in the reservoir water column and measured external influences on stratification (meteorological and hydrological).

Meteorological data

As discussed in Section 3.5, one of the current limitations to a detailed understanding of the stratifying and mixing processes in Pindari Dam is the lack of frequent (Pindari Dam BOM station) and representatively accurate (Inverell Research Centre BOM station) meteorological data available at the reservoir. Meteorological conditions are a core influence on both stratification and natural mixing within a reservoir. The more accurately this data represents the conditions at the surface of the reservoir, the better understood the intricate influences on these processes are.

In terms of modelling stratification, the following parameters can be considered necessary:

- Wind speed and direction
- Air temperature
- Solar radiation
- Relative humidity (necessary in the sense that it is an input into AEM3D, the relative sensitivity is unknown)
- Cloud coverage (potentially already accounted for in BOM recorded data)

Additional parameters that are beneficial to modelling and an understanding of the reservoir system include:

- Atmospheric pressure (can be calculated from readily available sea-level records)
- Rainfall (considered more important for water balance, as opposed to directly affected stratification)

The frequency of recording is a crucial component of beneficial meteorological data. For example, while Pindari Dam station records the most representative data, the temporal variations captured by the Inverell Research Centre station are more valuable to understanding changes in the reservoir system. At a minimum, all datatypes excluding solar radiation and rainfall should be collected at a 3-hourly frequency (current recording frequency for data available at BOM stations considered representative for Pindari). This would:

- Provide short enough temporal variations to observe the diurnal changes to meteorological conditions and their respective influence on the stratification in the reservoir.
- Represent the minimum requirement for data to be used in modelling and be reasonably representative of diurnal variations, given the interpolation required for modelling.
- Allow for optimised, varied flow rates of a bubble plume destratification system responding to diurnal variations of the meteorological data.

Ideally, an automatic weather station would be used to collect all these meteorological parameters every 15 minutes. The station would be set up as close to the surface of the reservoir as practically possible to ensure data collected is representative of the conditions directly influencing stratification. This would:

- Provide a detailed dataset with which the intricate influences of each meteorological condition on stratification could be explored.
- Provide accurate and representative input conditions for numerical modelling, increasing the reliability of the model to represent in-reservoir conditions.
- Guarantee, through automation, a consistent and high-frequency data set obtained at a remote location.
- Allow for further optimisation of flow rates and operational procedures for a destratification system at a smaller time-step, should this be practical.

Bathymetric information

Should updated bathymetric information be unavailable, it would be beneficial to conduct a survey of the current Pindari reservoir bathymetry. While it is unlikely that there have been any significant bathymetric changes that are not captured in the DEMs, an accurate bathymetry would provide more certainty to the design of the pipe distribution network which is to be anchored along the thalweg of the reservoir.

Appendix D provides a summary of all the data and information that would benefit the assessment of the impacts of stratification and cold water pollution at Pindari, as well as the design of mitigation options.

4 Bubble plume destratification in Pindari Dam

After considering all of the previously presented information regarding cold water pollution, mitigation options and the observed impacts of stratification at Pindari Dam (Prentice *et al.*, 2021; Chaaya and Miller, 2022), WRL recommended that a bubble plume destratification system would be the most appropriate mitigation strategy to trial in a pilot study. Given the existing multi-level offtake and selective withdrawal capabilities at Pindari, designing a bubble plume destratification system for the reservoir presented an opportunity to compare the effectiveness of each strategy. Based on the historical downstream river temperature records (see Section 3.4), selective withdrawal was clearly only an effective strategy when other conflicting protocols (such as blue-green algae transport mitigation) were not in effect. Theoretically, artificial destratification could be effective in instances where blue-green algae counts were high, potentially mitigating the issue of blooms altogether. Based on WRL's previous literature review (Chaaya and Miller, 2022), surface mixers would likely be incapable of effectively mixing Pindari reservoir given its significant depth and volume. While surface mixers might be capable of mitigating cold water pollution in some capacity, there is little evidence to suggest they would mitigate all the impacts of stratification highlighted in the review.

This section details the methodology behind the preliminary design of a bubble plume destratification system for Pindari, including:

- Numerically derived static flowrates for long- and short-term destratification strategies.
- Numerical modelling (conducted by Griffith University) of a destratification system in Pindari using these static flow rates in the AEM3D model.
- Draft operational procedures considering varying flowrates based on simplified meteorological data.
- Compressor, delivery pipeline and diffuser pipeline network design based on the applied flowrates.
- Energy requirements and remote renewable energy source design.

Given the complexity and dynamic nature of the internal and external factors that affect stratification in a reservoir, additional data for model calibration, verification and detailed design should be collected. However, the investigations presented here provide enough confidence in the airflow and destratification requirements to proceed to a pilot study.

4.1 Design air flowrates methodology

Air flowrate is key to the overall design of a bubble plume destratification system. Should the selected flowrate be too low, the system would be incapable of overcoming strong stratification. Should the flowrate be too high, the system will unnecessarily waste energy in the destratification process. The design flowrate affects both the operational (energy requirements) and capital (compressor requirements) costs of the system. This was apparent in all of the reservoirs considered in our literature review.

The methodology for bubble plume design outline by (Schladow, 1992, 1993) was used to determine the flowrate required to destratify Pindari reservoir. This methodology defines the isothermal work of compression (W_{iso}) required to completely destratify a reservoir in a stratified state, based on the difference in the potential energy (PE) of the system in both states. This considers a mechanical efficiency (η_{mech}), which represents the capability of the destratification system to convert the work input by the compressor to work done to destratify the reservoir, such that:

$$\eta_{mech} = \frac{PE_f - PE_i}{W_{iso}}$$

Where PE_f is the potential energy of the destratified system and PE_i is the potential energy of the stratified system.

To determine these PE values, the reservoir is separated into any number of layers with defined volumes based on the depth of the layer and the aforementioned stage-storage curve. There is no strict definition of the depth of each layer, however detailed design should consider the thermal structure of a stratified reservoir and the rate of change with increasing depth. The PE of the stratified reservoir is determined by summing the PE of each of these layers considering the varying density structure based on the varying thermal structure:

$$PE_i = g \times \sum \rho_{l,strat} \times V_l \times h_l$$

Where g = gravitation constant, V_l = volume of layer l, h_l = height of the mid-point of layer l above the bed and $\rho_{l,strat}$ = density of layer l based on the water temperature in the layer (T_l), such that:

$$\rho_l = 0.0001T_l^3 - 0.009095T_l^2 + 0.0679T_l + 999.84$$

The theoretical PE of the same system in an unstratified state is determined based on the average density of the stratified system:

$$PE_f = g \times \rho_{avg} \times \sum V_l \times h_l$$

Where:

$$\rho_{avg} = {\sum V_l}\Big/{\sum \rho_{l,strat} \times V_l}$$

To determine W_{iso} required to destratify the reservoir, the mechanical efficiency (η_{mech}) needs to be determined, using the dimensionless variables M (representing source strength) and C (representing stratification strength) with the below Figure 17 proposed in Schladow (1992).

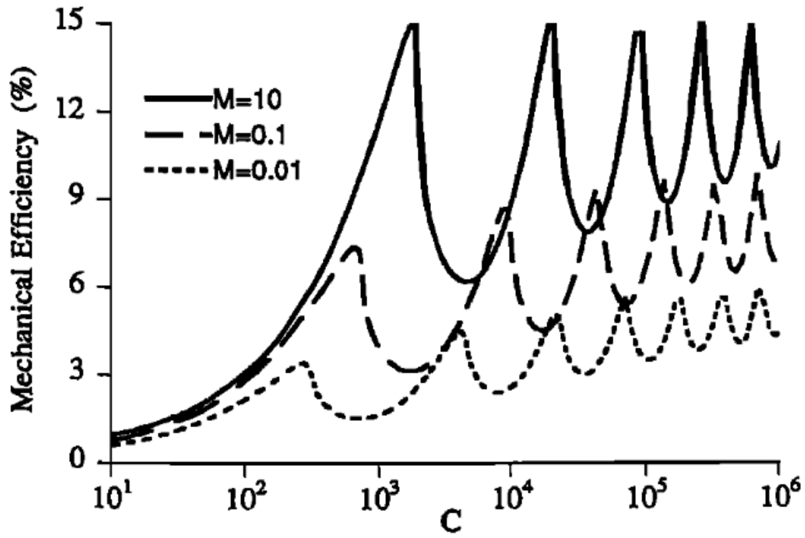

Figure 17 Mechanical efficiency chart (Schladow, 1992)

Figure 17 presents that the maximum efficiency is approximately 15% but can dramatically reduce to around 3% depending on the ratio of airflow rate to stratification.

M and C are defined using the equations in Table 5.

Table 5 Equations for dimensionless variables M and C

Equations	Constants
$M = \frac{Q_0 \rho_a (\lambda^2 + 1)}{4\pi \alpha^2 \rho_r H^2 u_b^3}$	Q_0 = total free air flow rate ρ_a = atmospheric pressure ρ_r = average density (unstratified state) $\lambda = 0.3$ = dispersion term $\alpha = 0.083$ = entrainment coefficient
$u_b = u_s(\lambda^2 + 1)$	u_b = buoyant velocity $u_s = 0.3\ ms^{-1}$ = bubble slip velocity
$H = h_a + h_w$	H = total head $h_a = 10.2\ m$ = atmospheric head h_w = water head
$C = \frac{N^3 H^4}{g Q_0 h_a}$	$g = 9.81\ ms^{-2}$ = gravitational constant
$N = \left(-\frac{g}{\rho_r} \times \frac{d\rho}{dz}\right)^{0.5}$	N = buoyancy frequency $d\rho$ = change in density from surface to bed dz = depth of water

The flow rate (Q_0) required to destratify the stratified reservoir over a chosen period of time (Δt) can be determined using:

$$W_{iso} = 2.303 \rho_a Q_0 \Delta t \ \log \frac{h_a}{H}$$

Both this and the mechanical efficiency are depending on a chosen air flow rate (Q_0), so an iterative process must be undertaken to determine the correct airflow rate. This can be performed using the following:

1. Determine the temperature profile in the stratified reservoir.
2. Determine the period over which destratification should occur.
3. Calculate the flow rate required to destratify the reservoir in this time, based on the required input with an assumed mechanical efficiency.
4. Calculate M and C for the flowrate used. Determine the mechanical efficiency of this system based on Figure 17.
5. Adjust the flowrate to achieve the desired time to destratify based on the new mechanical efficiency.
6. Repeat steps 3 – 5.

After determining the total airflow rate, further iteration may be required on the diffuser design.

4.1.1 Limitations of methodology

The methodology outlined attempts to numerically simplify a complicated and dynamic environment and processes. Limitations of the methodology include:

- Flow rates are based on a single, static temperature profile. In reality, the thermal structure of the reservoir water column will not be static, especially when subject to artificial destratification.
- Flow rates are based on a static destratification period. This does not consider changes to the thermal structure of the water column subject to artificial destratification that will occur over the destratification period.
- The methodology does not account for further stratifying energy introduced to the system over the destratification period.

4.2 Preliminary Pindari design airflow rates

Based on the previously outlined methodology, WRL produced a number of design flowrates for a destratification system in Pindari.

4.2.1 Assumptions

A number of assumptions and simplifications were applied based on previous experience with stratification in reservoirs and knowledge ascertained from the literature review. Assumptions and simplifications were largely considered conservative for this initial design, as they represent the reservoir in a static state.

Destratification period

Two periods for destratification were used. Six (6) days were chosen as representative of the time period over which stratification would re-develop from a completely destratified system. In reality, this period is completely dependent on the meteorological hydrological inputs to the reservoir, and would therefore be entirely dynamic. Six (6) days can be considered an overestimation, to account for the continuous heating that is not accounted for in the methodology. Thirty (30) days was chosen as representative of the time period over which gradual and continuous destratification could be applied. By choosing a longer time period, lower flow rates could be applied to investigate the effects of long-term destratification strategies.

Temperature gradients

Two temperature gradients were considered. Two degrees Celsius (2°C) was chosen to represent only slightly stratified conditions. A difference between the surface and bed temperature of 2°C might trigger the operation of a destratification system. Flow rates calculated under this assumption represented the necessary flow rates to maintain a destratified reservoir through continuous operation of a destratification system, the idea being that the gradient should never increase above this threshold. Eight degrees Celsius (8°C) was chosen to represent a standard temperature gradient in stratified conditions. The maximum natural stratification observed in Pindari is approximately 14°C (Section 3.6.1) which is greater than the 8°C used in the calculations. As such, the duration to destratify the reservoir may be longer than the 30 days in the worst case.

The destratification system proposed for the potential pilot study at Pindari Dam would be designed to operate continuously and commence prior to the onset of stratification. The aim would be to maintain isothermal (i.e. < 2°C stratification) over the whole summer period. With appropriate fail-safes (TBD), higher temperature gradients may not need to be considered in design. It is, however, necessary to consider the worst-case scenario (i.e. 8°C or more stratification) in the case of total system failure at this preliminary stage.

Compressor capacity and port diameter

A compressor pressure capacity of 10 bar was chosen, to allow sufficient pressure to overcome the ~73 m of total pressure head at the diffuser depth. A port diameter of 3 mm was chosen to balance head loss, the effects of nozzle diameter of bubble size and the effect of bubble size on dissolution into the surrounding water (Sahoo and Luketina, 2003).

These values governed the number of ports required based on pneumatic limitations of the diffuser design, and consequently the mechanical efficiency to which these systems could perform.

Reservoir capacity

For simplicity, the flowrates were determined under the assumption that the reservoir was at 100% capacity. This can be considered a conservative estimate, as the required flow rate will decrease as the capacity of the reservoir decreases. Varying reservoir water levels should be considered in the detailed design for the purposes of optimising the flow rates.

4.2.2 Design flowrates

Table 6 outlines the various flowrates that could be applied, along with the conditions under which they could be effective.

Table 6 Air flowrates required to destratify Pindari reservoir under varying conditions

Q (L/s)	# nozzles	ΔT (°C)	Destratification period (days)	Conditions
2,500	320	8	6	Breaking established destratification over a short period.
500	70	8	30	Breaking established destratification over a long period.
730	102	2	6	Varying flow rates, designed to maintain destratified conditions over varying periods.
500	70	2	8	
350	50	2	14	
250	36	2	16	
200	29	2	20	
150	22	2	30	

2,500 L/s is considered the necessary flowrate to break established stratification over a short period, based on the aforementioned assumptions. This represents the worst-case scenario. For the proposed Pindari destratification pilot study, this flowrate would only be required after total system failure. The design will likely incorporate fail-safes (e.g. multiple compressors) to avoid this scenario.

500 L/s is considered the necessary flowrate to maintain a mixed water column, based on the aforementioned assumptions. This best represents the operational goals of the proposed Pindari destratification pilot study. The system would commence operation prior to the onset of stratification and maintain a destratified reservoir over the usual stratification period.

4.2.3 Historical success check

As part of the cold water pollution literature, a library of cases where surface mixer and bubble plume destratification had previously been used was put together. The previously outlined 500 and 2,500 L/s flowrates can be compared to these historical records of success and failure, to provide a secondary check and ensure that the flowrates considered aren't too low.

Figure 18 shows instances of successful and unsuccessful attempts at destratification where air flowrates were available in literature. The y-axis represents the capacity of the reservoir (in ML) and the x-axis represents the ratio between the air flowrate used (in L/s) and reservoir capacity. Colours (indicated by the legend) indicate instances where destratification was successful, unsuccessful or partially successful in raising temperatures through the water column and at the bed of the reservoir. As a general rule of thumb, an air flowrate to reservoir capacity ratio greater than 0.01 has generally resulted in successful destratification.

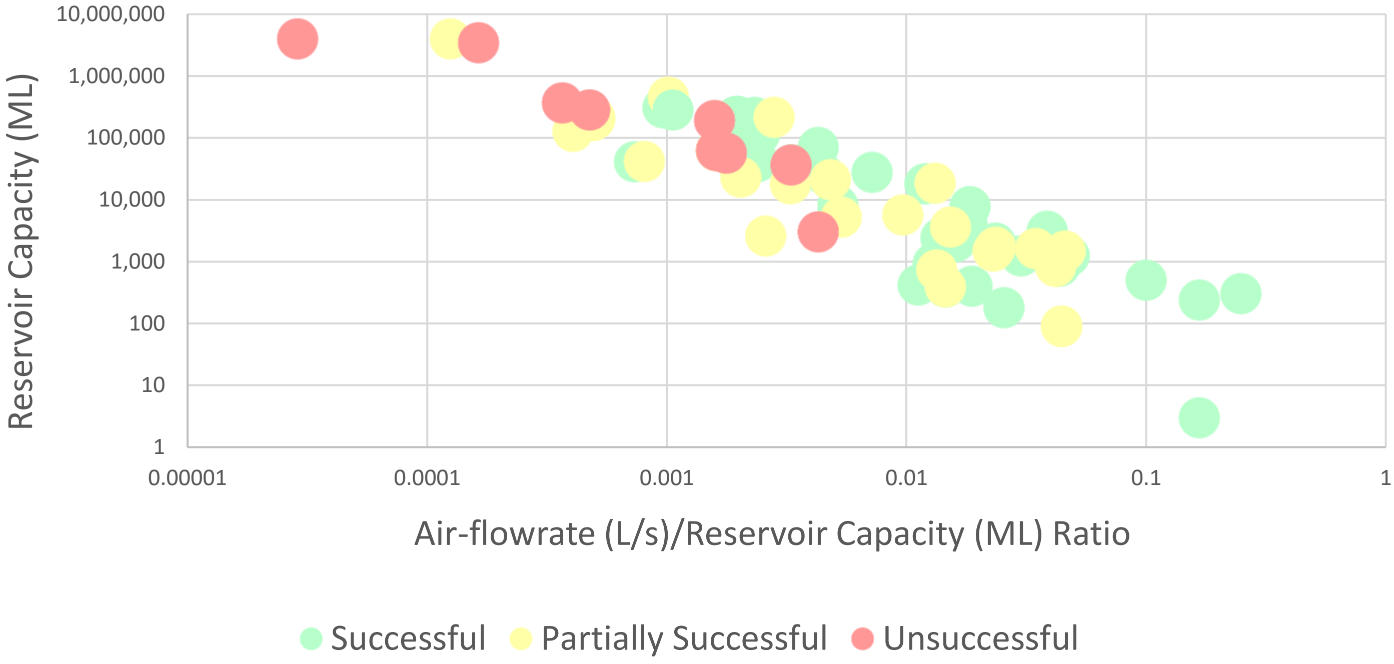

Figure 18 Reservoir capacity vs. flowrate to capacity ratio – demonstrating historically successful attempts at destratification

Given a maximum Pindari reservoir capacity of ~312,000 ML:

- 2,500 L/s represents a flowrate to capacity ratio of ~0.008
- 500 L/s represents a flowrate to capacity ratio of ~0.0015

This preliminary judgement of success is more important for examining the upper limit of flow rates, as a 500 L/s flow rate will be achievable with a variable speed drive (VSD) system capable of producing 2,500 L/s. Considering where the 2,500 L/s ratio fits into the plot, it is likely the selected upper limit flow rate of 2,500 L/s is capable of destratifying a reservoir the size of Pindari. It falls short of 0.01 ratio outline previously, however it is still in the range of a number of successful attempts.

4.3 Three-dimensional modelling of Pindari

4.3.1 Pilot modelling study of Pindari

In tandem with the investigations undertaken by WRL, Griffith University undertook a pilot modelling study of Pindari. This work investigated the capability of AEM3D to model stratification in Pindari and the potential effects of destratification using the flowrates outlined in Section 4.2.2. The reader is referred to the final report prepared by Griffith University, *Cold Water Pollution (CWP) mitigation options assessment for Pindari and Copeton*, for a detailed summary of the AEM3D modelling results.

The report specifically highlights that this model was not calibrated due to a lack of in-reservoir temperature profile data over the study period. While the results of this study provide a

reasonable indication of the effects of the outlined flowrates, further data is required to assess the validity of modelling results.

In the case of breaking established stratification, both the short- and long-term scenarios were successful in increasing temperatures near the bed by up to 5°C. The short-term destratification (2,500 L/s over 6 days) was capable of warming down to the bed at a faster rate, however the long-term destratification (500 L/s over 30 days) maintained slightly warmer temperatures at the bed for an extended period. Where established stratification is required to be broken, it may be beneficial to employ the larger flow rate to effect a change over a shorter period and reducing this flow rate under destratified conditions. 2,500 L/s was demonstrated to be capable of breaking stratification at different times throughout summer, including mid-summer where stratification was at its peak.

In maintenance conditions (i.e. continuous operation), a number of flow rates from 200 L/s up to 500 L/s were demonstrated to increase the temperatures to the bed of the reservoir. Increasing flow rate resulted in:

- A shorter period to initiate warming water at the bed of the reservoir
- Further breaking down of the microstratification occurring at the surface of the reservoir
- Increased overall temperature in the water column and at the bed

While the 500 L/s airflow rate was effective in increasing temperatures near the bed up to ~ 23°C, stratification was still observed through the hottest period of the year. In considering cold water pollution mitigation alone, this may be satisfactory. Should destratification be seen as a potential tool to mitigate other water quality issues caused by stratification in reservoirs, high flow rates may be required under sustained high-temperature meteorological conditions. This highlights the necessity of having a higher capacity system with a VSD to effectively maintain isothermal conditions year-round.

The continuous operation of a 4,000 L/s capacity surface mixer was modelled. This strategy performed poorly and did very little to affect stratification in the reservoir. Stratification continued to develop over the summer period, and minimal heating was observed at the bed of the reservoir as a result.

These preliminary numerical modelling studies suggest:

- Bubble plume destratification is a feasible strategy for mitigating cold water pollution at Pindari Dam.
- Surface mixers are likely to be inadequate as a standalone solution to mitigating cold water pollution at Pindari Dam.
- 2,500 L/s is likely an adequate maximum capacity for the case of system failure and stratification developing.
- 500 L/s will likely be adequate for continuous operation initiated before the onset of stratification, to ensure the reservoir remains destratified over an entire summer.
- A continuously operated strategy to maintain destratified conditions should be adopted as a baseline, with the capability to run increased flowrates in the case of an emergency.

4.4 Preliminary sensitivity analysis of AEM3D

Detailed design of a numerical model and bubble plume destratification system were not undertaken as part of this report. Instead, sensitivity analysis of the AEM3D model was carried out with idealised thermodynamic and meteorological conditions. Sensitivity analysis made use of the model structure and input files provided by Griffith University. The reader is referred to Griffith University's modelling report (Prentice *et al.*, 2021) for details. Two key modifications were made to the aforementioned Inverell Research Centre BOM station data used as meteorological inputs to the model:

- An 80% reduction factor was applied to wind speeds to account for the relatively steep topography around Pindari which would likely moderate wind speeds and affect wind direction. In instances of missing data, gaps were filled with linearly interpolated U and V speed and direction components.
- An 80% reduction factor was applied to the total daily solar radiation measured at the Inverell BOM station, to account for likely shading by the relatively steep topography around Pindari. To satisfy the input units (W/m^2) required by the AEM3D model, Griffith University converted the daily total solar radiation (MJ/m^2) to hourly solar radiation using the R package 'insol' and a cosine transfer function.
- Rainfall was omitted from the temporally varying meteorological inputs due to uncertainty in catchment runoff. Instead, measured and modelled water levels were balanced using additional temporally varying inflows and outflows. This ensured the measured water levels were accurately represented within the modelling process.

The current sensitivity analysis considered where future detailed design might further optimise the operation of a destratification system. This included:

- The effects of varied bubble air flow rates on short-term destratification of a reservoir in a significantly stratified state. This would demonstrate the potential worst-case scenario (i.e. breaking established stratification under extreme meteorological conditions).
- The potential optimisation of bubble air flow rates based on idealised modelling of representative meteorological conditions. This would demonstrate where operation might be optimised based on a live feed of meteorological data.

4.4.1 Effects of varying bubble air flow rates

The results of the Griffith University Pindari modelling study demonstrated the effects of varying flowrate on the speed and effectiveness of destratification. As expected, for the same conditions, increasing air flowrates was shown to:

- Destratify the reservoir faster
- Result in a greater increase to bed temperatures

Modelling was undertaken by WRL to further exemplify these effects using idealised conditions. AEM3D was initiated with two (2) different temperature profiles representing established maximum stratification and maintenance (i.e. destratified) conditions.

Established maximum stratification

The first model was initiated with a stratified temperature profile extracted from the Pindari base-case modelling results, representing the maximum possible stratification that occurred through the study period (2016/2017 summer). It is important to note that this could be considered an unreliable indicator of the worst-case scenario (i.e. maximum stratification) as the model was not calibrated. Profiles available between 1997 and 2001 (see 3.6.1) demonstrate lower temperature gradients than the profile used, however maximum temperatures were significantly higher in the study period (up to 42.8°C). It was concluded that, while unverified, the modelled profile from a year with extreme temperatures would better represent the worst-case scenario.

A range of airflow rates between 500 and 20,000 L/s were applied continuously to the reservoir over the 7 day period to observe the changes in stratification based on varying flowrates. The heat exchange module was disabled in AEM3D for these runs, which essentially limits any external additional heating of the reservoir through meteorological conditions. This demonstrated the isolated effects of destratification on a stratified water column, and represents the static input limitations of the airflow rate methodology. Table 7 summarises these results:

Table 7 Effects of varying airflow rates (over a 7 day period) on a strongly stratified reservoir with no external meteorological or hydrological input

Q (L/s)	$T_{surf,I}$ (°C)	$T_{bed,I}$ (°C)	DT_i (°C)	$T_{surf,f}$ (°C)	$T_{bed,f}$ (°C)	DT_f (°C)
20000	32.8	12.9	19.9	22.4	19.8	2.6
10000				23.2	19.3	3.9
5000				24.6	17.9	6.7
3000				26	16.4	9.6
2000				27.3	15.3	12
1500				28	14.7	13.3
1000				29.6	14	15.6
500				32	13.4	18.6

Note that the bed temperature was extracted from 4 m above the bed, to ensure the effects of the diffuser at 2 m above the bed were observed over such a short period of time.

The results of this modelling demonstrate that the previously suggested maximum 2,500 L/s airflow rate for breaking established stratification could increase bed temperatures by ~ 3°C over 7 days. Higher airflow rates would destratify at a faster rate, however the cost-benefit trade-off for a significantly larger compressor may not be viable.

Maintenance conditions

An identical approach was taken with an idealised initial temperature profile representing the mixed water column with 2°C of stratification. This is essentially representative of the original simplifications made for the maintenance case. Table 8 summarises the results of these test.

Table 8 Effects of varying airflow rates on a "mixed" reservoir with no external meteorological or hydrological input

Q (L/s)	$T_{surf,I}$ (°C)	$T_{bed,I}$ (°C)	DT_i (°C)	$T_{surf,f}$ (°C)	$T_{bed,f}$ (°C)	DT_f (°C)
20000	24	22	2	22.8	22.2	0.6
10000				22.8	22.2	0.6
5000				22.8	22.1	0.7
3000				22.9	22.1	0.8
2000				22.9	22.1	0.8
1500				22.9	22.0	0.9
1000				23.0	22.0	1
500				23.1	22.0	1.1

These results demonstrate the minimal value gained out of increasing flowrates to what would be considered an excessive amount. While 10,000 and 20,000 L/s results in the largest decrease in the temperature gradient, the change is only 0.5°C more than that achieved by using 500 L/s. It is likely that 500 L/s is all that is required to maintain destratification in Pindari. Consider that these results don't account for the introduction of heat through external meteorological conditions, which may vary the temperature changes observed.

The cost-benefit balance of choosing a maximum compressor capacity (i.e. maximum achievable flow rate) is important to the viability of bubble plume destratification. Consideration should be given to the potential worst-case scenario conditions, as these have been a common historical failure mechanisms of bubble plume destratification as a strategy (as highlighted in the literature review and Figure 18). If a system is incapable of breaking stratification under specific, extreme conditions, the benefits of using bubble plume destratification over selective withdrawal might not be realised.

4.4.2 Varying bubble air flowrates based on live data

The ability to vary air flowrates based on measured meteorological and hydrological data will be a key component of a fully optimised bubble plume artificial destratification system. This higher level and detailed design is beyond the scope of this current works undertaken in this report. Figure 19 provides a basic outline of the feedback loop that might adjust flowrates accordingly with measured data.

Figure 19 General feedback loop for operating a bubble plume destratification system with optimised and automated air flowrates

WRL undertook preliminary investigations into the potential for optimised airflow rates through modelling stratification in AEM3D under idealised meteorological conditions. The 2016/2017 stratification period was used due to the occurrence of extreme maximum temperatures through summer. Conditions representing a hot, moderate and cool day were selected for each season in which stratification is commonly observed (spring, summer and autumn). The choice of representative conditions was based on the total global daily exposure, as this results in the largest input of heat to the system, with consideration given to maximum air temperature, cloud coverage and wind speed. Each of the 24-hour timeseries of meteorological conditions were repeated for a total of 7 days and used as an input to the model. A full 24-hour timeseries for each of these days can be found in Appendix E

Each season-specific model run was initiated with a default water temperature and isothermal conditions in the water column (see Table 9). These were qualitatively assigned, based on the 1997 to 2001 profile data and modelling results obtained through the Griffith University modelling study, to represent the potential average temperature in a mixed water column for each season. By starting the model in an isothermal state, the effects of idealised meteorological conditions could be quantified over the modelling period.

Each set of conditions was modelled over a 7 day period. The profile representing the maximum temperature gradient was extracted from these results and used to determine the flowrate required to destratify the reservoir over the same 7 day period (using the methodology outlined in Section 4.1). This essentially represented the flowrate required to completely negate 7 days-worth of stratifying conditions, theoretically resulting in a completely mixed water column. Table 9 summarises these model runs and result.

Table 9 Calculated flowrates for a Pindari Dam destratification system under various idealised meteorological and hydrological scenarios

Season	Initial water temperature (°C)	Day-type	Representative date	Total global daily exposure (MJ/m^2)	Maximum temperature* (°C)	Flowrate required (L/s)
Spring	16	Hot	21/11/2016	30.39	29.7	1,790
		Moderate	08/09/2016	17.63	20.8	300
		Cool	29/09/2016	4.86	14.1	0
Summer	22	Hot	30/12/2016	31.43	34.0	1,720
		Moderate	15/02/2017	25.43	29.9	1,100
		Cool	28/02/2017	15.03	24.1	230
	16	Hot	30/12/2016	31.43	34.0	2,130
Autumn	19	Hot	02/03/2017	24.72	29.0	1,170
		Moderate	02/04/2017	15.72	23.3	170
		Cool	28/05/2017	5.66	17.2	0

**Maximum temperature according to BOM. This may not have been captured directly as part of the 3-hourly measurements provided by the BOM and thus may not appear in the meteorological data timeseries outlined in Appendix E*

These results show significant variability in the theoretical airflow rate required to destratify various reservoir conditions. This highlights the potential for detailed design to optimise a bubble plume destratification system. Variable flow rates present an opportunity to minimise operational costs. While 500 L/s has been demonstrated to adequately warm bed temperatures to an acceptable temperature, the Griffith University and WRL modelling studies showed that it may not be effective in completely destratifying Pindari under certain meteorological conditions (i.e. representatively hot days). This is an important consideration if the destratification system is to be considered a tool to mitigate other potential water quality issues caused by stratification in Pindari.

The results demonstrate the effects of the temperature of the water on the conduction of heat to the reservoir at the surface air-water interface. The idealised spring and summer “hot” days produce similar theoretical flow rates, despite increased air temperatures and solar radiation for the summer conditions. This can be partly attributed to the lower initial water temperature in the spring conditions. An additional model run for the summer conditions was run to further exemplify this interaction. This used identical meteorological conditions with a lower initial temperature equivalent to the spring conditions and resulted in an increase of required flow rate of 410 L/s.

5 Energy, operation cost and capital costs estimates

WRL's literature review highlighted ongoing operational costs as a historically limiting factor for successful artificial destratification. These limitations were more frequently observed with increasing reservoir capacity (as per Figure 18), likely due to the significant energy requirements necessary to maintain destratification in large reservoirs. In assessing the feasibility of a destratification in a large capacity reservoir such as Pindari, it is important to evaluate the potential energy requirements, inherent operational costs and capital costs of a compressor capable of producing the flowrates previously outlined.

WRL undertook preliminary investigations into:

- Potential off-the-shelf compressor systems capable of destratification in Pindari
- Estimations of the total energy required to maintain destratification over a single year
- Estimations of the expected operational and capital costs incurred

5.1 Compressor

Based on the results of the numerical investigations undertaken in this study, the minimum requirements for a compressor capable of destratification in Pindari Dam include:

- 500 L/s air flowrate – minimum required to maintain acceptable destratification in Pindari
- Variable speed drive – to adjust flowrates based on the monitored in-reservoir and meteorological conditions
- 10 bar (or higher) operating pressure – to overcome hydrostatic pressure in the deepest part of the reservoir
- Oil-free – to minimise the environmental and ecological impact of the system

A 315 kW air compressor would meet these requirements. The capital costs of such a system (excluding installation fees, transport etc.) is in the order of $500,000 AUD.

5.2 Energy and operational costs

A 315 kW compressor producing 500 L/s would have to commence operation prior to the onset of stratification (early Spring) and operate continuously over most of Spring, Summer and Autumn to effectively maintain destratification in Pindari. It is assumed that this is roughly 210 days/year under 24 hours/day operation. This is equivalent to 5,000 hours/year.

This results in a total of 1,600,000 kWH each year.

At an assumed price of $0.25/kWh, this equates to operational costs in the order of $400,000 AUD/year. The unit price of electrical power requires further investigation and will be dependent upon many local factors.

5.3 Additional costs

The estimated costs outlined above only cover the purchase and operation of a compressor. A number of additional costs would be incurred to implement a fully operational destratification system in Pindari Dam. These costs have not been estimated at this stage, as they are subject to the optimisation of:

- Operational procedures
- Acceptable levels of risk (in terms of system failure)
- Distribution and diffuser pipeline pneumatics
- On-site limitations
- Renewable energy supply

Additional costs will include:

- Installation and maintenance of:
    - Compressor
    - Distribution and diffuser pipeline
    - Monitoring network
    - Renewable energy farm
- Materials for the distribution and diffuser pipeline
- Instrumentation required for a monitoring network
- Power infrastructure (depending on the location of a renewable energy farm and grid connection requirements)

5.4 Assumptions and scaling

The costs and energy requirements presented consider the operation of a single compressor capable of 500 L/s. As per the results presented in this study (Section 4.2.2), up to 2,500 L/s may be required to effectively break established stratification in the worst-case scenario (total failure of the system). Additionally, idealised scenario testing (Section 4.4.2) highlight the importance of being able to achieve flowrates between 500 and 2,500 L/s for effective maintenance of destratification (as opposed to simply warming release temperatures). The current energy and cost estimates should be considered the bare minimum required for a destratification system in Pindari Dam.

Should the Pindari destratification system be designed to operate at the upper 2,500 L/s air flowrate, it is likely that a series of smaller capacity compressors would be utilised (in part, to provide a potential failsafe to the failure of a single compressor). Costs of this system would scale linearly with the maximum airflow rate required. For example, a system with a maximum air flowrate capacity of 2,500 L/s might use five (5) 500 L/s. If, hypothetically, these were required to operate year-round at 2,500 L/s, the operational costs would be in the order of $2,000,000 AUD/year (5 x $400,000 AUD).

Additionally, the energy requirements outlined assume 24 hour/day operation. It may be beneficial to operate the system for only 12 hours/day If solar renewable energy is to be considered. This would effectively double the airflow rate and compressor flowrate capacity required to produce the same amount of destratification work (Section 4.1).

6 Summary and discussion

Cold water pollution presents a serious environmental and ecological concern for rivers downstream of large storage reservoirs. Pindari Dam is no exception, historically causing significantly lower than natural water temperatures in the Severn River system downstream. This occurs during periods of stratification in the reservoir. A multi-level offtake tower currently operates to mitigate cold water pollution from Pindari Dam, however historical gauged downstream temperature data indicates that this strategy is not consistently effective. Instances of cold water pollution from Pindari Dam are likely due to algae discharge protocols which over-ride cold water pollution discharge protocols. These initiate when regularly measured concentrations or biovolumes of blue-green algae exceed a red alert threshold, at which time protocols dictate the withdrawal depth be lowered to minimise their entrainment in release waters. Generally, in stratified conditions, this withdrawal depth draws water from below an establish thermocline, resulting the discharge of cold water.

The UNSW water Research Laboratory was approached to explore the feasibility of artificial destratification as an alternative to selective withdrawal as a means of mitigating cold water pollution. Through an extensive literature review, it was concluded that bubble plume destratification was the only strategy that could mitigate both cold water pollution, increase water quality in a reservoir and potentially reduce algae growth. Historical success with bubble plume destratification has been varied. A number of limitations of previous attempts were identified:

- In some larger reservoirs, insufficient airflow rates were used resulting in inadequate mixing and destratification. The assumption here is that airflow rates were limited due to significant operational costs.
- The success of bubble plumes in limiting algae growth was highly varied, however success was more commonly found in deeper reservoirs. This was likely due to mixing algae from surface waters into deeper waters where light does not penetrate which in turn limits algal growth.

Pindari Dam was chosen as the most appropriate site for a preliminary desktop investigation and pilot in-situ trial due to the unique combination of reservoir shape, depth, capacity and an existing multi-level offtake. WRL had previously provided DPI Fisheries with preliminary theoretical flow rates that might be used for the design of a bubble plume destratification system in Pindari. These flow rates and their respective uses were:

- 500 L/s – baseline maintenance flowrate, capable of maintaining destratified conditions in the reservoir if initiated prior to the onset of stratification.
- 2,500 L/s – the maximum flow rate required to break established stratification within a reasonable period. This would likely only be required in the instance of a system failure, where stratification was able to establish.

Concurrent work undertaken by Griffith University made use of these flowrates as part of a numerical modelling study, to further explore the feasibility of bubble plume destratification. Their results showed the capability of a system operating with these flow rates to maintain and break established stratification over a historically hot summer.

Further modelling undertaken by WRL, using the model established and shared by Griffith University, explored the sensitivity of model predictions and destratification to varied flow rates and idealised meteorological conditions. This work further highlighted the potential for flowrates to be optimised while also providing confidence that 2,500 L/s (provided in the preliminary assessment) would be the upper limit of flowrates.

The limitations of the modelling and other desktop analysis tools are recognised. This report highlights the significant gaps in data required to build, calibrate and verify a model with a higher level of confidence. The current, uncalibrated model (due to a lack of supporting meteorological and hydrological data) can be considered uncertain. It should be considered a tool to demonstrate the feasibility and potential for bubble plume destratification as a strategy to mitigate cold water pollution downstream of Pindari Dam.

To improve on the current understanding of the system, WRL recommends the installation of a monitoring network specifically tailored to collecting data relevant to stratification and artificial destratification in Pindari reservoir. Consistent and sub-diurnally varying:

- Meteorological data should be collected close to the reservoir surface, to best represent the conditions that directly affect the natural mixing and heat exchange at the air-water interface.
- In-reservoir temperature and other water quality profile data (such as blue-green algae concentrations, dissolved oxygen) should be collected in several locations, to closely monitor variations to these conditions as a result of both natural and artificial influences.

Data is key to refining, calibrating and verifying the current model of Pindari. Increased modelling accuracy would allow further refinement of the design airflow rates and specific optimisation of the operational protocols to minimise operational costs. This would potentially feed into the design of a solar renewable source of energy for the destratification system, shifting a significant proportion of the expected operational costs to capital costs.

Monitoring of conditions before any destratification trials take place will provide the necessary baseline data for pre- and post-destratification assessment of cold water pollution. Monitoring during destratification trials will allow optimisation of airflow rates in real time. Ongoing monitoring after initial trials, will allow for data to be incorporated into active operational controls.

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Appendix A Review of Stage One and Two of the NSW Cold Water Pollution Strategy

1 September 2022

WRL Ref: WRL2021057 BMM FC LR20220901

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Dear Matthew,

Cold Water Pollution – Review and Assessment Planning
Task 1: Review of Stage One and Two of the Cold Water Pollution Strategy

1. Introduction

The Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney has been engaged by NSW Department of Primary Industries (Fisheries) to review and summarise previous work on cold water pollution mitigation in NSW undertaken by the Cold Water Pollution Interagency Group and to undertake an assessment for opportunities and future trial cases. In parallel with this investigation, WRL has undertaken an international literature review of cold water pollution and artificial destratification techniques (Chaaya and Miller, 2022).

This letter report provides a systematic review of the previous stages (Stage One and Stage Two) of the NSW Cold Water Pollution Strategy (the "Strategy") which includes:

- Reviewing all available previous reports and outputs
- Preparing an independent review report

Where not specifically referenced, findings in this letter report have come from:

- *Cold Water Pollution Strategy in NSW: Report on the implementation of stage one* (NSW Cold Water Pollution Interagency Group, 2012)
- *Report on the implementation of Stage 2 of the NSW Cold Water Pollution Strategy* (New South Wales Government, 2017)

2. The Framework of the Cold Water Pollution Strategy

A key objective of the *Water Management Act* 2000 is the protection of water sources and their associated ecosystems. In response to this objective, the State Water Management Outcomes Plan (SWMOP) was developed under the Act (and gazetted in 2002). The SWMOP contained targets which required water managers in NSW to address cold water pollution. These specific targets are listed in Table 1.

In response to the SWMOP, the NSW Cold Water Pollution Strategy was adopted by the NSW Government in 2004. At the time, cold water pollution was recognised as the second most significant impact arising from the operation of State dams (the primary issue being flow regulation). The Strategy acted to address a significant environmental issue that impacts the protection of water sources and their associated **ecosystems**, and noted that unless cold water pollution was addressed that improvements expected in river health as a result of water sharing plans may not be realised.

SWMOP targets were to be addressed through actions carried out over the 25 year life of the Strategy, which was subsequently broken down into five-year stages.

Table 1 - SWMOP targets pertaining to cold water pollution

Target	Description
Target 26	*Dams responsible for cold water pollution identified, a priority listing prepared, and action initiated to ensure that the temperature regime below these dams is kept within the 20th to 80th natural percentile range for each month (or within bounds determined by site specific investigations), by ensuring:*
Target 26a	• *Structural modification of at least two priority dams*
Target 26b	• *Improved operational protocols established for priority dams with existing temperature management infrastructure*

Preece (2004) identified 28 dams for action out of a total of 3,000 dams and weirs assessed in NSW (Figure 1). Nine (9) dams were identified as high priorities for cold water pollution mitigation, with a further 14 listed as moderate and five (5) considered as displaying less severe impacts.

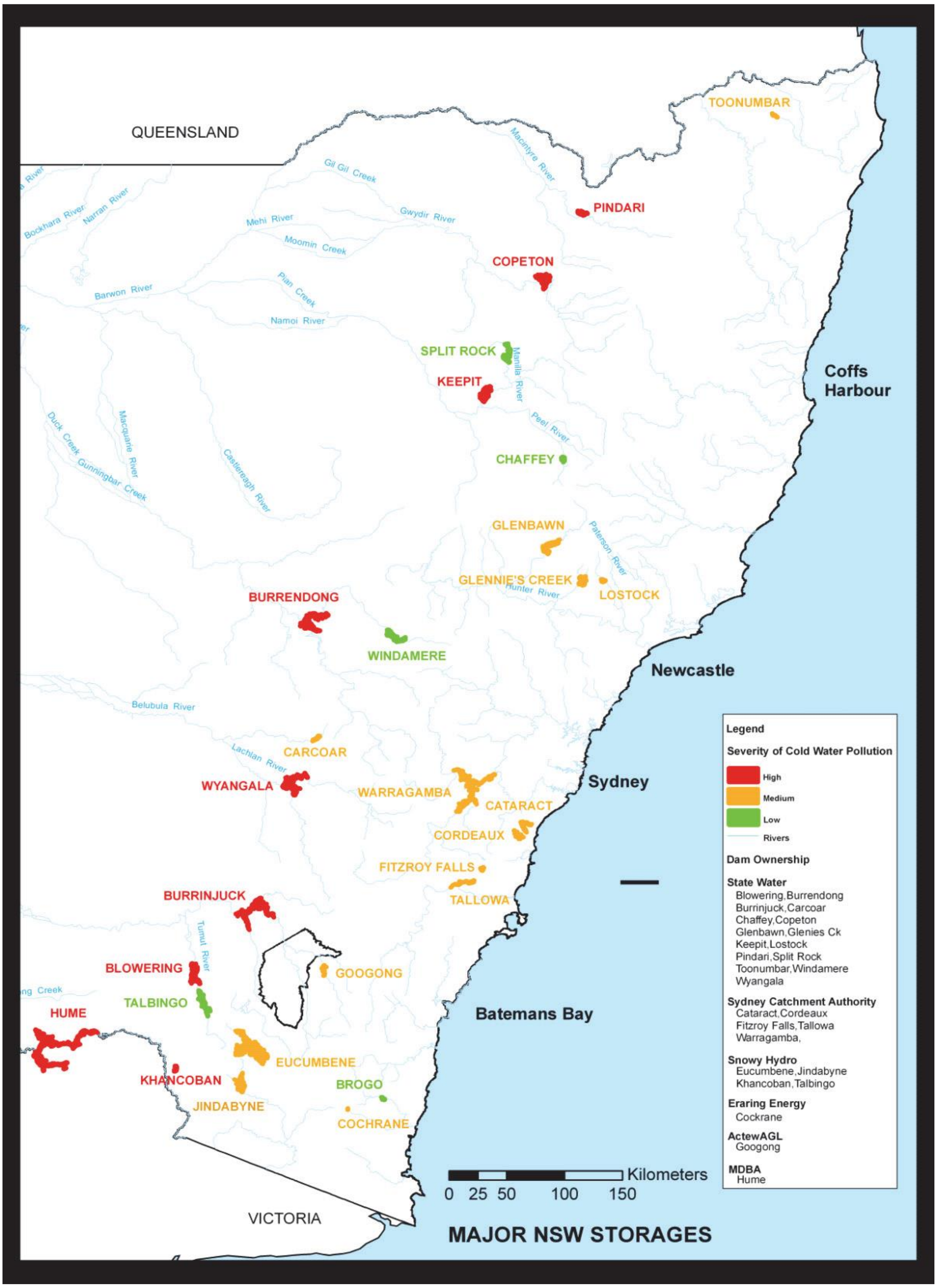


Figure 1 NSW dam identified for cold water pollution impacts, updated from Preece (2004) by CWPIAG (2012)

3. Stage One activities

Stage One of the Strategy aimed to address targets stipulated in the SWMOP, as well as to form the foundation for a monitoring and governance framework. Outcomes included:

- Recognising and prioritising dams causing severe cold water pollution.
- Planning and implementing cold water pollution mitigating infrastructure at priority dams.
- Developing and implementing operating protocols for dams with already existing multi-level offtake capabilities.
- Developing a governance framework and Cold Water Pollution Interagency Group (CWPIAG) to assist with the strategy.
- Providing a forum to achieve a coordinated, whole-of-government response to cold water pollution.
- Implementing and maintaining a temperature monitoring network.

The Terms of Reference (TOR) of the CWPIAG listed specific objectives to address these outcomes, including:

- Monitor implementation of actions identified as part of Stage One and outcomes achieved which include:
    1. Trial and verification of low cost solutions at Burrendong
    2. Implementation of works at Keepit Dam
    3. Implementation of works at Tallowa Dam
    4. Implementation of works at Jindabyne Dam
    5. Implementation of improved operating protocols at six (6) dams
    6. Implementation of structural modifications at six (6) dams
- Develop performance criteria and targets for releases from dams.
- Coordinate review of Strategy at end of Stage One and report outcomes to NSW Cabinet (via Water CEO's and Minister for Natural Resources).
- In consultation with dam owners, determine which dams are to be investigated in each subsequent 5 year stage of the Strategy.
- Identify critical issues and set parameters for each detailed dam investigation.
- Consider outcomes of each detailed investigation and in consultation with dam owners, agree on recommendations for the most suitable option for each dam.
- Regularly report to Water CEO's on Strategy progress.
- Prepare reports and present recommendations to NSW Cabinet (via Water CEOs and Minister for Natural Resources) regarding options, priorities and timeframes for priority dams over 20-25 years in 5 year stages.

WRL reviewed the Stage One report for actions and tasks reflecting the outcomes and objectives outlined above. Table 2 provides a summary of these, indicating the nature of their success in the scope of Stage One of the NSW Cold Water Pollution Strategy. A number of these actions were transitioned through to Stage Two, as discussed in the Stage One Summary following Table 2.

Table 2 Key tasks, recommended actions and outcomes as part of Stage One of the Cold Water Pollution Strategy

Outcome	Action	Completed	On track	Notes
Regulatory framework	Legislative amendments	Yes	-	*Water Managements Act* 2000 amended via insertion of Section 100(3) that enables the Minister to specify the dams where cold water pollution activities must be undertaken over a nominated time frame, monitoring and reporting on actions taken, and where specific ongoing operating protocols are to be implemented. Water CEOs made responsible for the implementation of the strategy; however, this group was later abolished with responsibility shifting to Senior Officers Group on Water. The CWPIAG managed Strategy implementation on a day-to-day basis, with TOR developed.
Evaluation of lower-cost options	Burrendong Dam	No	Yes	Modelling trials of design options completed indicating feasibility of thermal curtain. Concept design completed. Further design activities and construction delayed to Stage Two.
Cold water pollution mitigation works	Burrendong Dam	No	Yes	Initiation of works was dependent on finalisation of thermal curtain investigations to be conducted in Stage Two.
	Keepit Dam	No	Yes	Option development and evaluation completed. Preferred MLO option chosen. Construction of MLO scheduled to commence in 2011.
	Tallowa Dam	Yes	-	Bubble plume destratification successfully implemented (2005-2009) as part of cold water pollution mitigation works at Tallowa Dam. Bubble plume decommissioned upon completion of environmental flow release infrastructure upgrades (2009), which included fish passage and selective withdrawal capabilities that mitigated cold water pollution releases.
	Jindabyne Dam	Yes	-	Works completed at the dam offtake in 2006 to mitigate cold water pollution releases.
Other structural modifications	Implement modification at 6 dams with existing selective offtake capabilities	No	No	GHD proposals largely rejected by WaterNSW due to cost and/or operational constraints.

Outcome	Action	Completed	On track	Notes
Dam operations	Management guidelines	Yes	-	*Guidelines for Managing Cold Water Releases from High Priority Dams* developed. These would assist decision making in regards to: • Clarifying what is and is not CWP • Develop CWP mitigation infrastructure performance standards • Assisting dam operators to develop and assess site specific operating protocols for CWP mitigation Guidelines could not be tested through Stage One due to insufficient temperature infrastructure and data. Testing and development on guidelines were carried through to Stage Two.
	Work approvals	Partially	Yes	Matrix of work approval conditions completed. Cold water pollution conditions included in work approvals for seven (7) dams: Copeton, Keepit, Split Rock, Wyangala, Glenbawn, Glennies Creek, and Lostock.
	Develop and implement revised operating protocols at 6 dams with existing selective offtake capabilities	No	Yes	DPE Water developed draft protocols for Pindari, Chaffey, Split Rock and Windemere dams. WaterNSW developed draft protocols for Glenbawn Dam and Glennies Creek Dam. DPE Water rolled out dam works approvals with conditions to implement operating protocols. WaterNSW conducted trials at Glennies Creek Dam in 2009/10 irrigation season. DPE Water and WaterNSW identified monitoring network and data gaps that required resolution prior to implementing operating protocols at six (6) dams. WaterNSW advised that obligations under the Algal Strategy (RACC Plan) require releases below the thermocline during algal blooms, which opposes requirements for cold water pollution mitigation.
Temperature monitoring	Develop and install temperature monitoring stations	No	No	Basic monitoring needs identified (Hardwick et al., in prep) to guide planning and operation of cold water pollution mitigation infrastructure. Funding for monitoring infrastructure and ongoing maintenance and data collection was generally not achieved in Stage One. WaterNSW installed thermistor chains at Wyangala Dam and Blowering Dam in 2010.
Cost-Benefit Analysis	Undertake economic analysis of Stage One & Two activities	Yes	-	Assessment completed by Hill (2009) – determined a positive Net Present Value (NPV) of $15 M - $33 M and a Benefit Cost Ratio (BCR) of 1.74 – 2.64 for Stage One activities. Additional benefits beyond fish improvement such as recreational benefits due to improved water quality and habitat benefits were not quantified which would have resulted in a higher BCR.
Preparation for Stage Two	Identify priority dams for investigation	Yes	-	Dams identified and endorsed by Water CEOs (Copeton, Wyangala, and Blowering) for cold water pollution investigations.

Stage One Summary:

The primary achievements from Stage One were:

- Completion of cold water pollution works at two (2) dams: Tallowa, Jindabyne
- Investigation of upgrade works at two (2) dams: Burrendong, Keepit
- Legislative amendments to WMA 2000 to formalise the regulation of cold water pollution
- Development of *Guidelines for Managing Cold Water Releases from High Priority Dams*
- Development of governance structure to guide Strategy implementation
- Completion of cold water pollution Cost Benefit Analysis

Stage One actions carried forward to Stage Two were:

- Construction of an MLO at Keepit Dam and development of operating protocols.
- Finalisation of investigations into the Burrendong Dam thermal curtain including the assessment of operation and maintenance implications. Development of a program for construction and operation.
- Investigate two priority dams for CWP mitigation out of Copeton Dam on the Gwydir River, Wyangala Dam on the Lachlan River, and Blowering Dam in the Murrumbidgee catchment.
- Scope, cost, and implement a program to test and evaluate infrastructure operating protocols.
- Finalisation of operating protocols for six (6) dams that already have selective off-take capability: Pindari, Glenbawn, Glennies Creek, Windamere, Split Rock and Chaffey dams.
- Development of a monitoring program including progressing installation of required monitoring infrastructure.

New tasks identified by the CWPIAG for Stage Two were:

- Develop a monitoring, evaluation, and reporting (MER) strategy including funding the installation, data collection and maintenance of monitoring equipment and development of temperature growth models for priority dams to quantify the effectiveness of Strategy implementation.
- Standardise the economic approach to benefits and costs of mitigation measures to better cost and attribute value to future investigations and works.
- Develop the Strategy into a program to be rolled out over the next 5 to 20 year period.

Table 3 provides a summary of the new and carried-over tasks and activities undertaken as part of Stage Two, as discussed in the Stage Two NSW Cold Water Pollution report.

Table 3 Key tasks, recommended action and outcomes as part of Stage Two of the Cold Water Pollution Strategy

Outcome	Action	Completed	On track	Notes
Regulatory framework	Murray-Darling Basin Plan	-	-	Schedule 10 of the Basin Plan outlines the significance of water temperature outside natural ranges as a key river health stressor (Chapter 9), with a key cause being the release of stored water from large dams. The Basin Plan's target criteria is for the monthly median water temperature to be within the range of the 20^{th} and 80^{th} percentile of the natural monthly water temperature (Schedule 11 of the Basin Plan).
Assessments completed	Khancoban Dam	Yes	-	Investigations by Snowy Hydro Limited demonstrated Khancoban Dam produced minimal downstream cold water pollution impacts. The CWPIAG reviewed these findings and reclassified the dam from 'high priority' to 'no mitigation proposed'.
High Priority Dam Investigations	Copeton Dam	Partial	No	Three high priority dams endorsed for mitigation investigation in Stage Two. WaterNSW completed an options study at Copeton Dam, with further design development proposed in Stage Three.
	Wyangala Dam	No	No	Infrastructure investigations deferred to Stage Three.
	Blowering Dam	No	No	Infrastructure investigations deferred to Stage Three.
Cold water pollution mitigation works	Burrendong Dam	Yes	-	Thermal curtain successful constructed and installed as part of Stage Two for $3.8 M. Master's degree student investigated ecological effects of curtain (2013-2015). Testing of the curtain in Stage Two proved difficult due to low (drought) dam water levels.
	Keepit Dam	No	No	Concept designs developed for gated ports on existing dam outlets to provide MLO capabilities. Stage Three activities involve completion of detailed designs which were expected to begin in 2020.
Dam operations	Management guidelines	Yes	-	Evaluation of *Guidelines for Managing Cold Water Releases from High Priority Dams* indicated that the guidelines were not appropriate for application. The guidelines were revised to a 5 day rolling cumulative temperature anomaly. The new metric was to be tested in Stage Three for finalisation.

Outcome	Action	Completed	On track	Notes
Dam operations	Blue Green Algae	Yes		WaterNSW evaluated the operating constraints imposed on cold water pollution mitigation by the presence of Blue Green Algae in storages, wherein water is released from below the thermocline during algal blooms resulting in cold water pollution releases. Further assessment of algae and cold water pollution management interplay required for Stage Three.
	Work approvals	Partial	Yes	Cold water pollution conditions included in work approvals for nine (9) dams: Pindari, Copeton, Keepit, Split Rock, Burrendong, Windamere, Wyangala, Blowering, Burrinjuck, with some overlap with Stage One works approvals. WaterNSW agreed to monitoring obligations for works approvals in Stage Two for above dams. Operating and reporting conditions are incorporated into the Snowy Water Licence 2010 for Jindabyne and Tantangara Dams managed by Snowy Hydro Limited. Works Approvals for the Sydney drinking water supply dams of Cataract, Cordeaux and Warragamba consider the needs of drinking water supply as a priority to cold water pollution mitigation under the *Water Management Act* 2000.
	Develop, implement, and assess revised operating protocols at 6 dams	Partial	No	Operating protocols developed and tested for Pindari, Split Rock, Chaffey, Windamere, Glenbawn, and Glennies Creek where selective offtake capability already existed. Evaluation of revised operating protocols to determine their effectiveness in mitigating CWP was delayed to Stage Three.
Monitoring	Develop and implement MER Strategy	Partial	No	Progressively installed water temperature monitoring infrastructure (60+ HOBO© loggers; 10 continuous permanent loggers) around priority dams. Responsibility of maintaining network and data management passed to WaterNSW by DPE Water in July 2016. MER strategy yet to be developed or funded beyond installation of temperature loggers.
Develop Strategy	Develop 20 year+ Plan	Partial	No	Stage Three activities recommended for next 5 years. 20 year plan yet to be developed for Strategy implementation.
Cost-Benefit Analysis	Undertake economic analysis of CWP activities	No	No	No progress made on developing an economic analysis template to standardise the approach to evaluating the benefits and costs of cold water pollution mitigation.

Stage Two Summary:

The primary achievements from Stage Two were:

- Construction of the thermal curtain at Burrendong Dam, including monitoring of its effectiveness when in operation.
- Detailed investigation and re-classification of cold water pollution at Khancoban Dam.
- Continued installation and maintenance of temperature monitoring equipment at large water storages across NSW.
- Development and implementation of operating protocols for dams with multi-level offtakes to deliver best management in water temperature releases.
- Evaluation of the guidelines for managing cold water releases from high priority dams.

Stage Two actions planned to be carried forward to Stage Three were:

- Keepit Dam - Construction work on offtake were delayed to late 2020 following completion of the dam safety upgrade activities.
- Burrendong Dam - WaterNSW to conduct a full review of the operation and effectiveness of the thermal curtain including an updated operating protocol. Further post-graduate evaluation proposed.
- Copeton Dam - WaterNSW planned to undertake further investigations to develop a preferred solution.
- Wyangala Dam - WaterNSW planned to undertake further investigations to develop a preferred solution.
- Development of an economic analysis template to standardise the approach to evaluating the benefits and costs of cold water pollution mitigation for individual storages.
- Development of a monitoring, evaluation, and reporting (MER) strategy including funding the installation, data collection and maintenance of monitoring equipment for the priority dams to quantify the effectiveness of Strategy implementation.
- Testing the five day rolling cumulative temperature anomaly metric.
- Updating the NSW Cold Water Pollution Guidelines to assist with dam operation and reporting against works approval requirements in annual licence compliance reports.
- WaterNSW to develop a 20 year Asset Strategy to plan for the delivery of water supply infrastructure works including cold water pollution mitigation.
- WaterNSW to evaluate the operating protocols for dams that already have selective off-take capability for their effectiveness at reducing downstream cold water pollution.
- Evaluation of the impacts of blue-green algae on the effectiveness on cold water pollution mitigation strategies. Blue-green algae primarily limits the use of selective withdrawal due to conflicting management protocols.

Given the time elapsed between the completion of Stage Two (2015) and time of writing of this review (2022), these actions and objectives should be reviewed.

4. Summary of responsibilities and governance

Responsibilities of contributing parties were assigned as part of the Cold Water Pollution Strategy governance framework. These include:

- Water CEOs Group – responsible for implementing the Cold Water Pollution Strategy
    - This became the responsibility of the Senior Officers Group on Water, with the abolition of the Water CEOs Group

- Interagency Group – managed the implementation of the strategy on a day to day basis and reported back to the Senior Officers Group on Water
    - Originally convened under direction of the Minister for Infrastructure, Planning and Natural Resources (now the Minister for Lands and Water)
- DPE Water – coordinate the state's response to the Strategy

5. Summary of key Reports / Documents

A number of reports and documents were produced as part of Stage One and Two of the Cold Water Pollution Strategy. These include:

- NSW Cold Water Pollution Strategy – Report on the implementation of Stage One
    - https://water.dpie.nsw.gov.au/__data/assets/pdf_file/0009/456912/NSW-Cold-water-pollution-strategy-stage-one.pdf
- NSW Cold Water Pollution Strategy – Report on the implementation of Stage Two
    - https://www.researchgate.net/publication/319889854_NSW_COLD_WATER_POLLUTION_STRATEGY_Report_on_the_implementation_of_Stage_2_2010-2015_NSW_Cold_Water_Pollution_Interagency_Group_Cold_Water_Pollution_report_on_implementation_of_Stage_2_of_the_Cold_Water
- Options studies for Burrendong dam
    - GHD MLO options study - unsighted by WRL
    - Manly Hydraulics Laboratory physical 3D model study of floating curtain – unsighted by WRL
    - Thermodynamic study of Burrendong (Connell Wagner) – unsighted by WRL
- Options studies for Keepit Dam
    - Manly Hydraulics Laboratory thermodynamic study of Keepit – draft released by MHL, sighted by WRL
    - Manly Hydraulics Laboratory refined thermodynamic modelling study - unsighted by WRL
- Options studies for Tallowa Dam
    - Unsighted by WRL
- Guidelines for managing cold water releases from high priority dams
    - https://water.dpie.nsw.gov.au/__data/assets/pdf_file/0008/456911/NSW-Cold-water-pollution-strategy.pdf
- Operating protocols to mitigate cold water pollution for dams with multi-level offtakes
    - Unsighted by WRL
- Snowy Hydro Limited final report regarding reclassification of Khancoban from "high-priority"
    - Unsighted by WRL
- WaterNSW 20 year Infrastructure Options Study Rural Valleys – Summary Report
    - https://www.waternsw.com.au/__data/assets/pdf_file/0019/132616/20-Year-Infrastructure-Options-Study-June-2018.pdf

6. Summary of activities for high priority dams

Dam	Multi-level offtake	Activity
Pindari	Yes	Pindari was identified as one of six dams with selective withdrawal capabilities. Structural modifications to improve selective withdrawal functionality were proposed, however were deemed not to be required. Operating protocols designed to mitigate cold water pollution using existing selective withdrawal infrastructure were developed as part of Stage One. Operating protocols were further developed and tested as part of Stage Two. The success of these were not reported. Further improvements to these protocols were anticipated post-Stage Two with additional data collection.
Copeton	No	One of three high-priority dams identified for Stage Two by the CWPIAG priority matrix. WaterNSW completed options studies as part of Stage Two; however, further design investigations deferred to Stage Three.
Keepit	No	As part of Stage One, a range of investigations were undertaken to explore options for cold water pollution mitigation at Keepit Dam. It was decided that a multi-level offtake would be suitable. Construction of the multi-level offtake was delayed through to Stage Three.
Burrendong	No	Options studies to mitigate cold water pollution at Burrendong dam were carried out as part of Stage One. A thermal curtain was installed in 2014 as part of Stage Two. Assessment of the effectiveness of the thermal curtain was ongoing at the completion of Stage Two. WaterNSW confirmed in 2022 that the thermal curtain will be decommissioned due to ongoing maintenance issues that limit effective operation.
Wyangala	No	One of three high-priority dams identified for Stage Two by the CWPIAG priority matrix. Investigations into mitigation options at Blowering were not completed in Stage Two.
Burrinjuck	Yes	Burrinjuck was identified as having existing infrastructure (MLO) that could be utilised to mitigate cold water pollution. At the completion of Stage Two, operating protocols aimed at mitigating cold water pollution were not yet completed by WaterNSW.
Blowering	No	One of three high-priority dams identified for Stage Two by the CWPIAG priority matrix. Investigations into mitigation options at Blowering were deferred past Stage Two.
Hume	No	No actions were carried out for Hume Dam through Stage One and Two, as the dam's operations are controlled by the Murray-Darling Basin Authority and are outside of NSW government jurisdiction.

7. Dams considered priority due to Cold Water Pollution impacts

At the initiation of Stage One, 28 dams were identified as key contributors to cold water pollution in NSW (Preece, 2004). Offtake depth and discharge volume were used to categorise dams as high, moderate and low priority, as per the following figure.

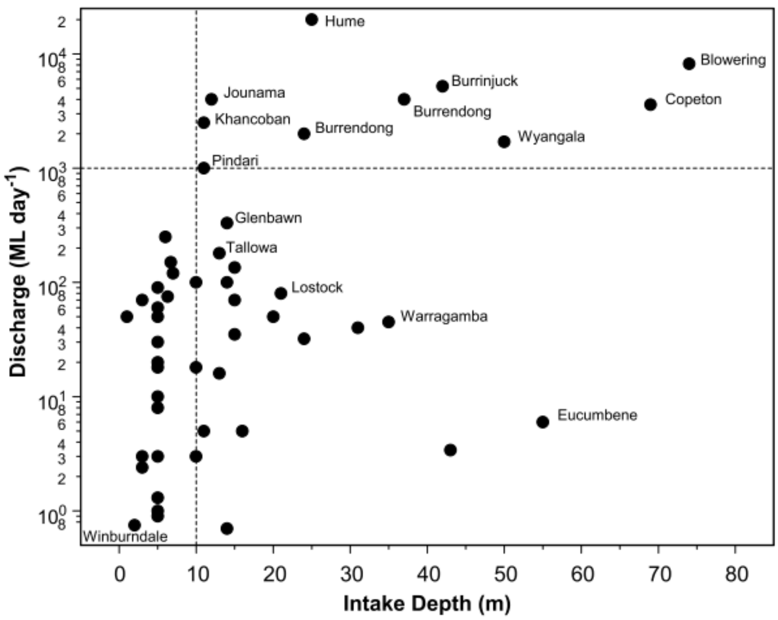


Figure 2 Cold water pollution impact severity and prioritisation based on intake depth and discharge (Preece, 2004)

As part of Stage One, the CWPIAG adapted these prioritisations and developed a priority evaluation matrix for identifying priority dams for Stage Two and beyond. The matrix, for each dam, considers:

- Size of problem – as per priorities defined in (Preece, 2004)
- Conservation and environmental values
- Practicality and opportunities
- Effectiveness of works
- Community factors
- Cost of preferred options

From Stage Two and beyond, the dams were to be prioritised under this scheme.

8. Operations and protocols for dams with existing Multi-Level Offtakes

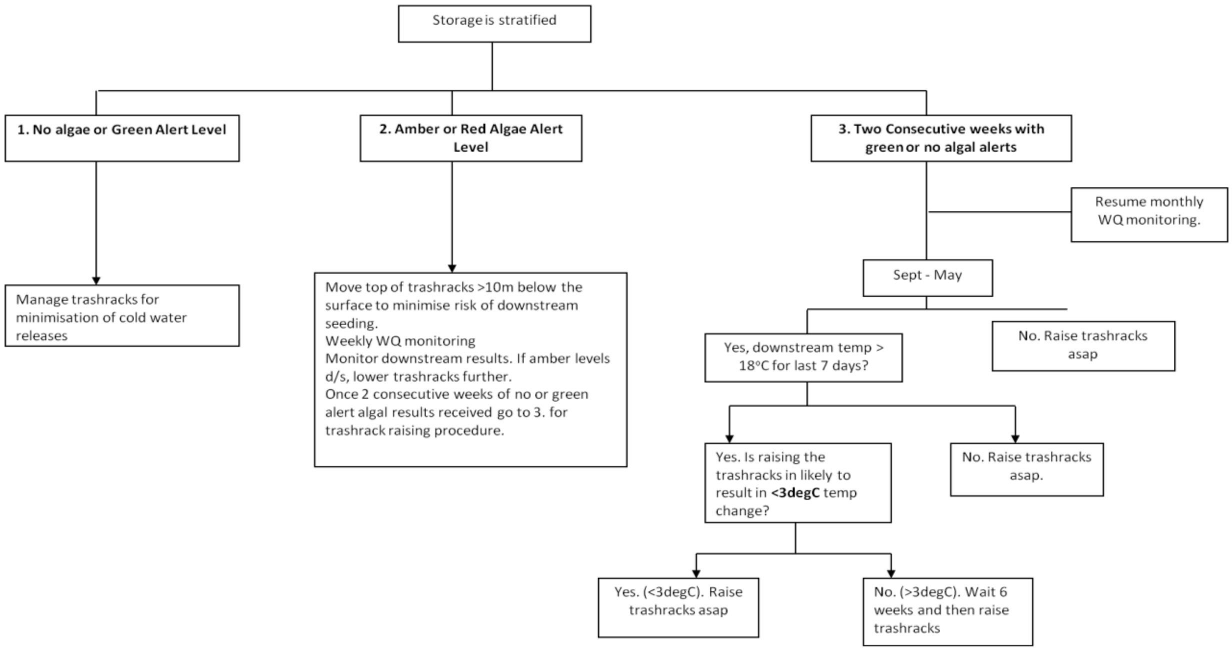
As part of the intended outcomes of Stage One, six (6) dams with existing MLOs were reviewed, with draft protocols developed to assist operators with mitigating cold water pollution. These dams were:

- Pindari Dam
- Glenbawn Dam
- Glennies Creek Dam
- Windamere Dam
- Split Rock Dam
- Chaffey Dam

The lack of consistent temperature data and a continuous monitoring network meant it was difficult for DPE Water and WaterNSW to implement and test these operational protocols as part of Stage One. As well as this, structural modifications to these MLOs for the purposes of improved protocols and cold water pollution mitigation were rejected due to cost and/or operational constraints relative to the anticipated benefits.

As part of Stage Two, operating protocols for the aforementioned six dams were developed, tested and used. Further improvements were expected as the protocols were reviewed, and better data is acquired. Updating the operating protocols was to tie in closely with the continually developing guidelines, which includes a better understanding of the operational effects of blue-green algae management relative to cold water pollution mitigation and the release of water from below the thermocline during algal blooms.

The following chart represents a generic set of operating protocols/guidelines for those dams fit with MLOs, extracted from (Hardwick *et al.*, 2011).



9. Guidelines for managing cold water releases from high priority dams

As part of Stage One, the CWPIAG developed guidelines for managing cold water releases from high priority dams. The guidelines aimed to:

- Provide guidance to dam operators responsible for the management of cold water pollution mitigation infrastructure (multi-level offtakes and destratification systems) to assist in the development of appropriate operating protocols.
- Provide guidance to engineers and designers evaluating and designing cold water pollution mitigation infrastructure, with particular attention to performance criteria.
- Clarify the definition of cold water pollution to assist with satisfactory performance of mitigation infrastructure.

The guidelines stipulated that dam asset managers would be granted works approvals on the basis of having implemented protocols for cold water pollution mitigation, rather than quantitative temperature outcomes. Future works approvals may need to consider ecologically-based guidelines.

Stage One original guidelines were for downstream releases to be within a percentile range of the "expected natural" temperature regime, derived from either:

- Field measurements collected prior to dam construction
- Measurements from local tributaries or upstream rivers outside the influence of the reservoir stored water

Hourly or daily averages were considered operationally unachievable. Monthly averages were adopted, however these were considered to have no ecological relevance. Subsequently in Stage Two, a 5 day rolling anomaly was suggested. The ecological validity of this method was not confirmed during Stage Two.

The guidelines outlined the need for baseline data and monitoring to effectively assess cold water pollution. These recommendations were partially implemented as part of Stage Two, with the introduction of a larger monitoring network of temporary and fixed temperature stations. Any review or improvements made to the guidelines should consider these data and monitoring requirements, and the expansion of the temperature logging network.

Further improvements to these guidelines should consider a realistic and operationally applicable definition of success. WRL's literature review (Chaaya and Miller, 2022) discusses the definition of success in terms of mitigating cold water pollution, and can be summarised by the following:

- Upstream and downstream temperatures are rarely consistent with each other in terms of magnitude and timing. The reservoir acts as a significant heat (energy) sink, resulting in variability of the temperature of water entering and being released from the dam. The significant volume of water contained in the reservoir results in time lags and daily variations between upstream and downstream temperatures.
- Ecological thresholds that affect fish physiology, behaviour and breeding patterns should be considered.
- An active artificial destratification system may be deemed successful if isothermal conditions are created.

10. Lessons learned from Stage One and Two

A number of lessons were learned through Stage One and Two of the NSW Cold Water Pollution Strategy. These are summarised below:

- Cold water pollution is a complicated issue, primarily arising from the thermal stratification of dams and the release of water from below an established thermocline. Part of the complication through Stage One and Two arose from a lack of in-depth understanding of:
    - Why dams stratify, and what controls stratification processes.
    - The optimum part of the water column to release water from and how to achieve this consistently.
    - In-reservoir algae management, mitigating algae release and how these operations conflicted with cold water pollution mitigation.
    - Quantification of the ecological impacts of cold water pollution.

    - The need for, costing of and operation of expensive mitigation infrastructure.
- The issue of cold water pollution management was larger and more complicated than the time allocated to fix or address it.
- There was a realisation that cold water pollution was an expensive issue to mitigate.
- Artificial destratification via bubble plumes was deemed an effective and proven approach, however high operating costs and associated carbon emissions limited its feasibility for further applications.
- Considerable weight was given to selective withdrawal methods, especially MLOs, despite their relatively high capital cost and inability to mitigate cold water pollution when algae management protocols were in effect.
- Attempts to mitigate cold water pollution with limited funding available were either ineffective or failed entirely.
- Quantitative metrics comparing upstream and downstream temperatures were:
    - Difficult to implement and monitor.
    - Not relevant or untested in terms of ecological outcomes.
    - Unachievable through the infrastructure and operating protocols used at the time.
- A lack of consistent and comparable data at the time made it difficult to quantify the effects of mitigation strategies and set achievable targets for dam managers.
- Economic analysis outlined basic monetary benefits of cold water pollution mitigation, however further detailed assessments were recommended to quantify potential realised benefits.

Moving forward, addressing the issue of cold water pollution must consider:

- Studies to assist with the understanding and quantification of the causes and impacts of cold water pollution.
- Achievable goals and targets that are:
    - Ecologically relevant.
    - Operationally feasible.
    - Easily implemented and monitored for their success.
- Alternative solutions to selective withdrawal infrastructure, due to clashing algae management protocols.
- Securing adequate resources and funding to ensure the outcomes of cold water pollution mitigation are met.
- A well maintained, on-going monitoring network collecting in-reservoir and downstream temperature data to quantify the effects of mitigation strategies and ensure targets are met.
    - Monitoring of additional water quality parameters (such as blue-green algae) should be considered, as this impacts the effectiveness of the mitigation strategy employed.
- Detailed economic cost-benefit analysis to quantify and realise the monetary benefits of cold water pollution mitigation, and justify the expected capital and operational costs.

11. Summary

Cold water pollution is a complex but important ecological and social issue to resolve. The impacts of cold water pollution in NSW have been recognised and reported on for almost 20 years. In this time, the issue has primarily been addressed through Stage One and Stage Two of the NSW Cold Water Pollution Strategy, which aimed to:

- Prioritise dams at which cold water pollution should be addressed.
- Implement cold water pollution mitigation infrastructure and operations at high priority dams.
- Develop a governance framework and Interagency Group to coordinate the implementation of the strategy and whole-of-government response to cold water pollution.
- Implement and maintain a temperature monitoring network.
- Develop guidelines and performance criteria to assist:
    - Dam managers in achieving mitigation goals.
    - Monitoring the implementation and success of mitigation operations.

Despite the recognition of the impacts of cold water pollution and actions undertaken to address the aims outlined above, progress over the course of Stage One and Stage Two was limited. This was primarily due to:

- A lack of understanding of the complexity of the issue.
- A lack of resourcing and funding for studies, monitoring and mitigation infrastructure.
- A lack of existing data and monitoring to achieve a better understanding of the complex issue.
- Difficulty implementing mitigation guidelines.
- Difficulty achieving the quantitative performance criteria included in the guidelines.

A number of actions and goals remain incomplete from Stage One and Stage Two of the strategy. These should be reviewed for any additional progress following the completion of Stage Two. Based on the limitations observed and lessons learned through this review of Stage One and Stage Two of the NSW Cold Water Pollution Strategy, ongoing mitigation works should focus on:

- Finalising a metric applicable to all high priority dams for the purposes of quantitatively measuring cold water pollution and mitigation measures. This should consider ecologically significant temperatures and thermal regimes, as well as the interplay between asset operation and quantifying compliance.
- Finalising guidelines including the previously mentioned metric. The dynamic nature of the guidelines thus far may have contributed to a lack of commitment to solutions.
- Updated protocols for existing multi-level offtake infrastructure based on the new cold water pollution metric.
- Developing an understanding of the operational limitations of the presence of blue-green algae in reservoirs, especially for selective withdrawal methods (multi-level offtake, thermal curtain).
- Exploring alternative mitigation strategies (artificial destratification) that present an opportunity to mitigate water quality degradation caused by stratification in reservoirs. Artificial destratification was largely ignored in favour of selective withdrawal methods due to the significant operational costs. These costs may be offset by additional benefits to water quality and the use of renewable energy.
- Performing an in-depth economic assessment of the benefits of mitigating cold water pollution, including previously considered ecological benefits, increased downstream water quality, and improved recreational value. If destratification is considered, a number of in-reservoir benefits should be realised, including recreational value, in-reservoir water quality, reduced evaporation

and algae mitigation. Renewable energy sources should be considered in this economic assessment.

Yours sincerely,

Brett Miller
Director, Industry Research

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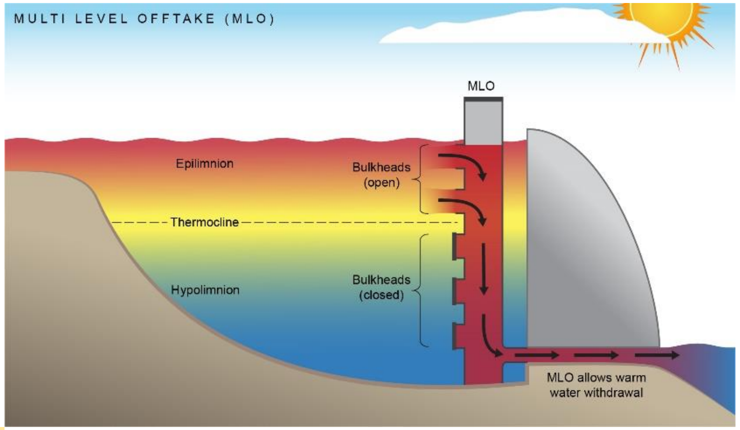
Appendix B Options summary

Selective Withdrawal: Multi-Level Offtake

Multi-level offtakes (MLO) enable selective withdrawal from different depths in the reservoir to improve the quality of release waters and mitigate downstream ecological and environmental impacts of reservoir stratification. Water can be selectively withdrawn from above the thermocline while the reservoir is stratified, to avoid cold water release and effectively mitigate cold water pollution (CWP). Operating protocols should consider the current state of stratification in the reservoir, to ensure effective withdrawal of warm surface water.

Selective withdrawal is more feasible for those dams with an already existing MLO structure, as retrofitting dams with this infrastructure can be of considerable cost.



Advantages:

- Successful operation can effectively mitigate CWP.
- Operations to mitigate CWP will avoid release of poor-quality water from below the thermocline in a stratified reservoir.
- Operationally lower cost than destratification.
- Potential for optimal automated operations based on live feedback from measured in-reservoir temperature and water level data.

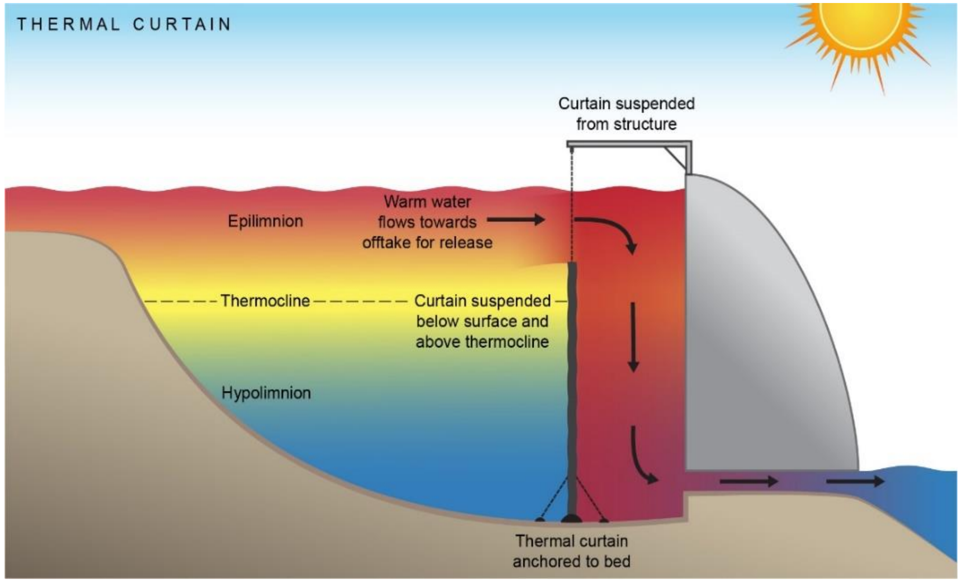
Disadvantages:

- If retrofitting an MLO is required, this option becomes considerably more expensive in regard to capital costs.
- Larger withdrawals can result in entraining waters from below the offtake depth, diminishing the effectiveness of CWP mitigation.
- Volumetric withdrawal requirements may be limited if CWP mitigation operating protocols are in effect, as these limit the depth from which water can be withdrawn.
- Conflicting requirements and obligations with the presence of blue-green algae in the reservoir.
- Rigid withdrawal depths may be problematic for varying water levels in a reservoir.
- Rapid changes from CWP mitigation to algae release mitigation protocols can result in significant ‘cold shock’ in the downstream river.

Most notable of the drawbacks of selective withdrawal is the presence of toxic cyanobacteria (blue-green algae) in reservoirs, which can severely limit the CWP mitigation capabilities of an MLO. Blue-green algae commonly dominates surface waters in reservoirs during warmer months, which coincides with large irrigation releases from storage dams. Operating protocols generally prioritise avoiding the downstream release of blue-green algae when cell count or biomass thresholds are exceeded, which requires withdrawing from a depth below the surface and often below the thermocline. This negates any ability to mitigate cold water pollution.

Algae mitigation protocols require immediate action to limit the release downstream. Rapid change from warm water release to cold water release in response to changing protocols may cause ‘cold shock’ to the downstream river environment, which can have significant negative ecological effects.

Selective Withdrawal: Thermal Curtains



Thermal curtains (sometimes referred to as 'screens') are an alternative to retrofitting MLO structures or modifying existing MLO structures for the purposes of CWP mitigation through selective withdrawal. This technique utilises a large, suspended curtain surrounding a current offtake tower or dam wall offtake extending from the bed of the reservoir to a depth below the surface. Curtains are made from a flexible material to allow height adjustments based on reservoir water levels and the presence of stratification. The material is impermeable and inhibits the passage of water anywhere other than between the surface and top of the curtain. This facilitates the release of warm surface waters in the event of a downstream release.

Thermal curtains generally boast the same advantages and limitations of a MLO. For a dam requiring a complete retrofit of infrastructure, a thermal curtain may be a desirable option based on the capital costs.

Advantages:

- Operations to mitigate CWP will avoid release of poor-quality water from a stratified reservoir.
- Significantly lower capital costs compared to retrofitting a MLO (estimations in the magnitude of 5-10 times cheaper).
- Potential for optimal automated operations based on live feedback from measured in-reservoir temperature and water level data.

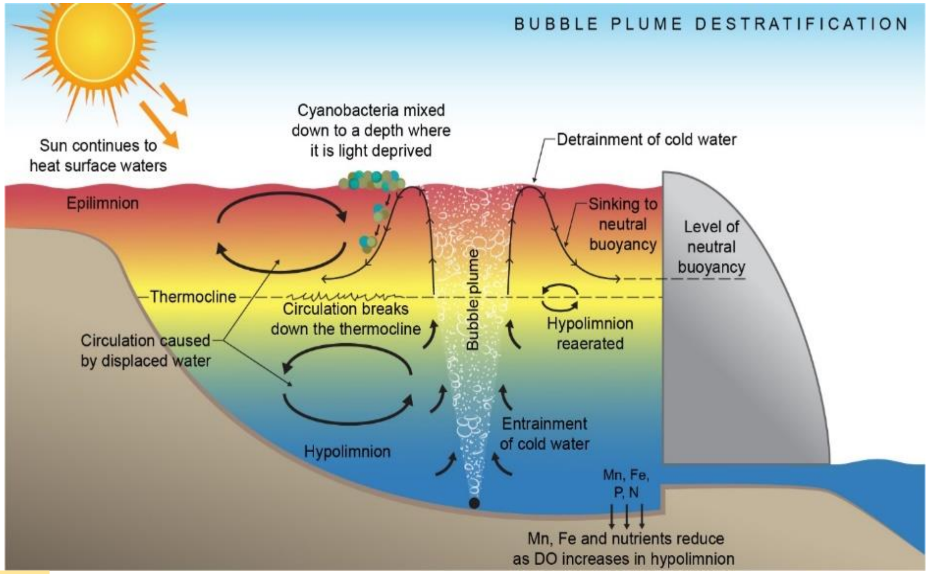
Disadvantages:

- Yet to be proven as an effective method to mitigate CWP (limited available data suggests only partial mitigation has been achieved).
- Not suitable for small volume releases, as long residence time or insufficient mixing between the curtain and withdrawal infrastructure may result in local stratification.
- Maintenance may be complicated, as the curtain is likely to be anchored to the reservoir bed.
- Conflicting protocols with the presence of blue-green algae in the reservoir.
- Rapid changes to operating procedures may result in significant 'cold shock' to the downstream environment.

As with a MLO, the presence of toxic blue-green algae in the reservoir is likely to be one of the more challenging operational constraints. Current guidelines indicate that the presence of significant blooms overrides any CWP mitigation protocols and requires the curtain to be lowered to a depth to allow withdrawal from below the surface. This is likely to result in the release of cold hypolimnetic water from below the thermocline and diminish the capability of the curtain to mitigate CWP. Rapid change from CWP to algae release mitigation protocols may result in significant 'cold shock' downstream of the reservoir.

Smaller withdrawals may dimmish the effectiveness of a thermal curtain for CWP mitigation. If the water within the curtain isn't 'cycled' regularly, it may stratify and negate any benefits.

Artificial Destratification: Bubble Plumes



This technique utilises rising bubble plumes to artificially break stratification in a reservoir. Typically, this involves pumping compressed air to the deepest part of the reservoir, where it is diffused through piping with drilled small holes. Rising plumes entrain cold, dense hypolimnion water to the surface, at which point it is detrained. Due to a variation in density, the detrained water sinks back to a depth of neutral buoyancy. From here, the water propagates laterally away from the plume, creating local mixing and dismantling the density structure and thermal stratification.

Bubble plumes have been successfully utilised in a number of reservoirs to break thermal stratification and effectively mitigate the impacts of CWP. These applications, however, have generally been limited to smaller reservoirs.

Advantages:

- Improve water quality in the reservoir system by breaking stratification and re-oxygenating anoxic hypolimnion waters.
- Can be an effective method of controlling blue-green algae by negating their buoyancy advantage and mixing to a depth where they become light-deprived.
- Redistributes temperature throughout water column homogenously, effectively mitigating CWP.
- Capable of achieving up to a 15% mechanical efficiency.
- Low-cost alternative in regards to capital investment.

Disadvantages:

- Operational costs can be significant for larger reservoirs, compared to selective withdrawal strategies.
- Large systems require a significant amount of power to operate, which may be unfeasible at remote locations.
- System maintenance can be complicated, given the piping network is usually anchored to the bed of the reservoir. Blockages or failures may be laborious to remediate.
- Insufficient destratification can lead to undesirable algae growth, as nutrients from the hypolimnion are entrained to the surface.

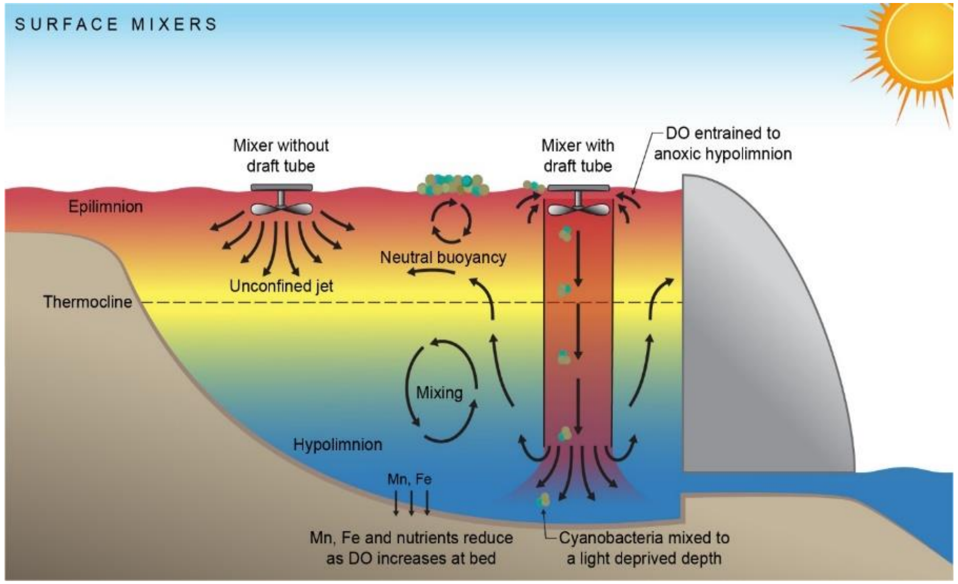
Bubble plume destratification is generally perceived as a low capital cost solution to mitigating the impacts of reservoir stratification (including CWP). The feasibility of these systems may diminish as reservoir size increases due to the significant operational costs. Given the minimal examples of successful applications in large reservoirs, further investigation is required to determine if bubble plume destratification is indeed an option for large irrigation storage reservoirs.

Blue-green algae presents a significant challenge for effective CWP mitigation through bubble plume destratification. If the system cannot successfully reduce blue-green algae growth in a reservoir, it may instead act to mix the toxic algae to the depth of an offtake, resulting in release downstream. Unlike selective withdrawal, artificial destratification has the potential to reduce algae growth and mitigate any issues toxic cyanobacteria may cause. This may be particularly beneficial in recreationally used reservoirs, where blooms prevent public access.

Artificial Destratification: Surface Mixers

Artificial destratification can also be achieved using mixers (impellors or propellors) located near the surface of a reservoir. Mixers are usually raft-mounted just below the surface of the reservoir, and work to either jet water down (more commonly) or draw water up through the water column. At the end of the jet, detrained water responds to the varied density structure and rises or sinks to a depth of neutral buoyancy. This creates mixing in the local vicinity of the of the mixer.

Systems are commonly accompanied by a draft tube, which assists to direct the jet to a desired depth. Draft tubes can be considered a necessity for the success of these systems for anything other than a very small reservoir. Without a draft tube, jets lose momentum and dissipate relatively quickly, diminishing the effectiveness of the mixer to destratify.



Advantages:

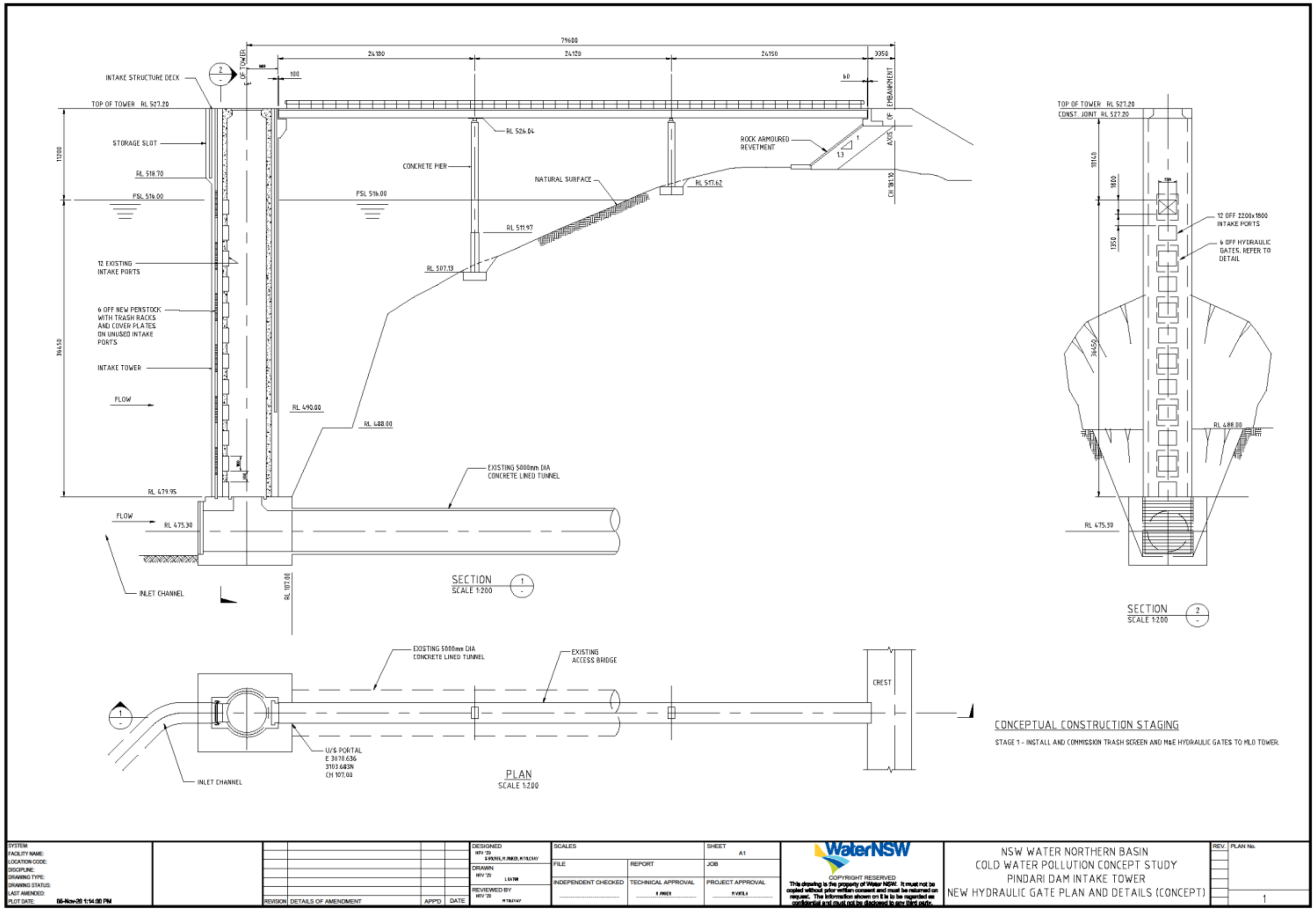
- Effective destratification can improve reservoir water quality, much like bubble plume systems.
- System maintenance is relatively easy compared to other options, as most of the system is accessible at the surface of the reservoir.
- May be effective for controlling blue-green algae, as a draft tube allows mixing to a specific depth.
- Low-cost alternative in regards to capital investment.

Disadvantages:

- Capable of a maximum mechanical efficiency of 12% (lower than bubble plumes).
- Jets penetrating close to the bed may scour, erode and resuspend bottom sediments.
- Circulation can be localised, and thus may not be effective for full reservoir destratification without a large network.
- Exposed system carries safety risk and susceptibility to vandalism.
- May have the negative effect of suppressing favourable algae species.

Surface mixers are commonly employed as “cost-efficient” alternatives to bubble plume destratification, due to their lower energy requirements and relatively good mechanical efficiency. There are, however, limited examples of successful application for CWP mitigation, especially in larger reservoirs. Due to their relatively localised effects, surface mixers may be feasible only in smaller dams with shallow offtakes. A network set up around the dam wall or offtake tower could be used to mix warm surface waters down specifically during a release event.

Appendix C Pindari offtake tower structural drawings



Appendix D Summary of information and data

Data Type	Data	Source	Use
Bathymetric and structural information	Reservoir bathymetry	WaterNSW	Modelling, design
	Offtake depth(s) and size	WaterNSW	
Hydrological	Reservoir storage volume and water level	WaterNSW	Modelling, design, water balance, stage-storage relationship
	Upstream flows and temperatures	WaterNSW	Modelling, water balance
	Downstream flows and temperatures	WaterNSW	Modelling, calibration and verification, design, water balance, cold water pollution assessment
Meteorological	Wind speed and direction	BOM	Modelling, design
	Air temperature	BOM	Modelling, design
	Relative humidity	BOM	Modelling
	Solar radiation	BOM	Modelling, design
	Atmospheric pressure	BOM	Modelling
	Rainfall	BOM, WaterNSW	Modelling, water balance
	Cloud coverage	BOM	Modelling
In-reservoir data	Temperature	WaterNSW	Calibration and verification, ongoing monitoring of an operational bubble plume destratification system, assessment of water quality
	Soluble metals (Mn, Fe)	WaterNSW	
	Dissolved oxygen	WaterNSW	
	Algae counts	WaterNSW	
Release strategies	Environmental flow releases	WaterNSW	Modelling, design
	Cold water pollution selective withdrawal	WaterNSW	Strategy comparison and specific scenario testing
	Downstream algae release mitigation	WaterNSW	Strategy comparison and specific scenario testing
Qualitative records and information	Historical blue-green algae bloom events	WaterNSW	Design, strategy comparison
	Operational/design limitations	WaterNSW/dam operators	Modelling, design

Appendix E Idealised model data

Season	Condition	Date	Initial Water Temperature (°C)
Spring	Hot	21/11/2016	16

Time-series data

Time	Wind Speed (km/hr)	Wind Direction (°)	Air Temperature (°C)	Relative Humidity	Solar Radiation (W/m^2)	Rainfall (mm)	Cloud Coverage
00:00	1.69	30	18.9	0.54	0	0	0.05
01:00	0.00	0	17.4	0.6	0	0	0.05
02:00	0.00	0	16.3	0.64	0	0	0.0375
03:00	0.40	160	15.8	0.73	0	0	0.0375
04:00	1.69	170	15.2	0.79	0	0	0.025
05:00	1.69	150	15.2	0.78	84.688	0	0.025
06:00	1.69	160	17	0.7	249.816	0	0.0125
07:00	1.20	150	19.6	0.53	402.416	0	0.0125
08:00	1.69	50	22.2	0.39	534.84	0	0
09:00	1.20	10	24.4	0.26	640.448	0	0.025
10:00	1.69	30	25.8	0.28	713.936	0	0.0375
11:00	2.09	50	26.8	0.21	751.624	0	0.0625
12:00	2.09	110	27.9	0.2	751.624	0	0.0875
13:00	4.09	90	28.4	0.18	713.936	0	0.1
14:00	3.29	40	28.7	0.16	640.448	0	0.125
15:00	3.69	60	28.8	0.16	534.84	0	0.1125
16:00	3.69	110	28.7	0.18	402.416	0	0.1125
17:00	3.29	80	28.1	0.16	249.816	0	0.1
18:00	2.49	60	26	0.24	84.688	0	0.1
19:00	1.69	20	24.1	0.28	0	0	0.0875
20:00	1.69	40	22.2	0.34	0	0	0.0875
21:00	1.69	150	19.6	0.39	0	0	0.075
22:00	1.69	150	19	0.41	0	0	0.075
23:00	1.69	90	18.2	0.5	0	0	0.0625

Season	Condition	Date	Initial Water Temperature (°C)
Spring	Moderate	08/09/2016	16

Time-series data

Time	Wind Speed (km/hr)	Wind Direction (°)	Air Temperature (°C)	Relative Humidity	Solar Radiation (W/m^2)	Rainfall (mm)	Cloud Coverage
00:00	0.80	80	11.5	0.79	0	0	0.3125
01:00	1.20	100	11.3	0.82	0	0	0.2875
02:00	2.49	80	11.2	0.82	0	0	0.275
03:00	1.69	100	10	0.87	0	0	0.25
04:00	2.09	110	8.6	0.93	0	0	0.225
05:00	0.00	0	9.2	0.87	0	0	0.2125
06:00	1.69	90	9.5	0.86	0	0	0.1875
07:00	1.20	20	11.5	0.79	79.216	0	0.1625
08:00	1.69	110	13.3	0.71	231.224	0	0.15
09:00	2.89	70	16.6	0.61	364.504	0	0.125
10:00	4.56	80	17.2	0.5	468.248	0	0.2125
11:00	3.29	30	18.1	0.43	534.064	0	0.2875
12:00	3.29	20	18.6	0.43	556.608	0	0.375
13:00	3.69	10	18.9	0.43	534.064	0	0.4625
14:00	2.89	30	19.1	0.42	468.248	0	0.5375
15:00	2.89	20	20.4	0.4	364.504	0	0.625
16:00	3.29	70	19.4	0.42	231.224	0	0.625
17:00	2.09	30	18.2	0.46	79.216	0	0.625
18:00	2.09	50	16.6	0.51	0	0	0.625
19:00	1.69	40	16.1	0.51	0	0	0.625
20:00	1.20	110	13.9	0.65	0	0	0.625
21:00	1.20	90	13.7	0.72	0	0	0.625
22:00	0.00	0	13.8	0.73	0	0	0.625
23:00	0.80	50	13.3	0.78	0	0	0.625

Season	Condition	Date	Initial Water Temperature (°C)
Spring	Cool	29/09/2016	16

Time-series data

Time	Wind Speed (km/hr)	Wind Direction (°)	Air Temperature (°C)	Relative Humidity	Solar Radiation (W/m^2)	Rainfall (mm)	Cloud Coverage
00:00	1.69	150	10.7	0.66	0	0	0.375
01:00	1.20	130	11	0.68	0	0	0.4125
02:00	1.69	10	11.7	0.64	0	0	0.4625
03:00	1.20	30	11.6	0.66	0	0	0.5
04:00	0.80	80	11	0.77	0	0	0.5375
05:00	1.20	10	11.9	0.72	0	0	0.5875
06:00	2.09	350	12.1	0.75	18.552	0	0.625
07:00	2.89	340	12.1	0.82	54.392	0	0.6625
08:00	4.56	10	12	0.91	86.52	0	0.7125
09:00	5.36	360	13.3	0.83	112.76	0	0.75
10:00	4.56	360	13.7	0.78	131.312	0	0.7875
11:00	4.96	360	12.3	0.94	140.912	0	0.8375
12:00	4.56	10	12.2	0.95	140.912	0	0.875
13:00	4.56	360	12.9	0.94	131.312	0	0.9125
14:00	4.96	360	13.6	0.92	112.76	0	0.9625
15:00	4.56	360	14	0.92	86.52	0	1
16:00	2.49	310	13.3	0.94	54.392	0	0.95
17:00	3.69	310	11.5	0.9	18.552	0	0.9
18:00	3.69	330	11.4	0.85	0	0	0.85
19:00	4.56	330	11.4	0.82	0	0	0.8
20:00	3.29	340	11	0.81	0	0	0.7625
21:00	2.49	350	9.4	0.91	0	0	0.7125
22:00	2.09	330	10.6	0.82	0	0	0.6625
23:00	3.29	330	10.5	0.63	0	0	0.6125

Season	Condition	Date	Initial Water Temperature (°C)
Summer	Hot	30/12/2016	22

Time-series data

Time	Wind Speed (km/hr)	Wind Direction (°)	Air Temperature (°C)	Relative Humidity	Solar Radiation (W/m^2)	Rainfall (mm)	Cloud Coverage
00:00	2.09	160	21.9	0.58	0	0	0.05
01:00	0.00	0	21	0.62	0	0	0.05
02:00	0.40	70	20.3	0.65	0	0	0.0375
03:00	1.69	360	20.1	0.64	0	0	0.0375
04:00	1.69	360	19.4	0.67	0	0	0.025
05:00	1.69	360	19.1	0.7	0	0	0.025
06:00	1.69	20	20.7	0.68	101.384	0	0.0125
07:00	2.09	30	22.7	0.65	298.248	0	0.0125
08:00	2.89	10	24	0.68	477.784	0	0
09:00	2.49	30	25.8	0.63	629.56	0	0.0375
10:00	2.09	20	27.4	0.56	744.736	0	0.0875
11:00	1.69	330	29.5	0.49	816.64	0	0.125
12:00	2.49	20	30.4	0.4	841.08	0	0.1625
13:00	2.09	70	31.7	0.39	816.64	0	0.2125
14:00	2.49	340	32.5	0.3	744.736	0	0.25
15:00	2.09	200	33.1	0.28	629.56	0	0.2625
16:00	1.20	50	32.9	0.3	477.784	0	0.2625
17:00	1.69	350	33.1	0.29	298.248	0	0.275
18:00	0.00	0	32	0.32	101.384	0	0.275
19:00	2.09	290	27.9	0.4	0	0	0.2875
20:00	2.09	300	28.3	0.36	0	0	0.2875
21:00	1.69	300	26.8	0.38	0	0	0.3
22:00	1.20	330	25.3	0.43	0	0	0.3
23:00	0.80	160	23.5	0.54	0	0	0.3125

Season	Condition	Date	Initial Water Temperature (°C)
Summer	Moderate	15/02/2017	22

Time-series data

Time	Wind Speed (km/hr)	Wind Direction (°)	Air Temperature (°C)	Relative Humidity	Solar Radiation (W/m^2)	Rainfall (mm)	Cloud Coverage
00:00	2.49	110	17.9	0.88	0	0	0.5375
01:00	2.49	70	18.2	0.84	0	0	0.525
02:00	1.69	10	17.7	0.88	0	0	0.5
03:00	1.20	340	17.3	0.9	0	0	0.475
04:00	2.09	340	17.1	0.92	0	0	0.4625
05:00	1.69	330	17.2	0.91	0	0	0.4375
06:00	0.40	330	16.1	0.97	82.008	0	0.4125
07:00	0.00	0	18.7	0.83	241.256	0	0.4
08:00	2.09	70	20.6	0.75	386.488	0	0.375
09:00	2.09	70	21.6	0.68	509.256	0	0.4375
10:00	2.89	100	23.5	0.61	602.432	0	0.5
11:00	2.09	40	24.8	0.57	660.592	0	0.5625
12:00	2.09	60	25.7	0.54	680.36	0	0.625
13:00	2.09	30	26.5	0.48	660.592	0	0.6875
14:00	2.09	50	27.9	0.46	602.432	0	0.75
15:00	2.09	10	28.7	0.38	509.256	0	0.7125
16:00	2.09	300	29.7	0.34	386.488	0	0.675
17:00	1.20	10	28.7	0.36	241.256	0	0.65
18:00	1.20	290	27.7	0.43	82.008	0	0.6125
19:00	2.89	110	24	0.63	0	0	0.575
20:00	2.89	80	22.6	0.66	0	0	0.5375
21:00	2.89	80	21.7	0.69	0	0	0.5125
22:00	2.09	70	20.8	0.74	0	0	0.475
23:00	2.49	70	19.8	0.76	0	0	0.4375

Season	Condition	Date	Initial Water Temperature (°C)
Summer	Cool	28/02/2017	22

Time-series data

Time	Wind Speed (km/hr)	Wind Direction (°)	Air Temperature (°C)	Relative Humidity	Solar Radiation (W/m²)	Rainfall (mm)	Cloud Coverage
00:00	2.09	150	16.3	0.8	0	0	0.925
01:00	1.69	140	16.5	0.79	0	0	0.925
02:00	1.69	150	16.1	0.82	0	0	0.9125
03:00	2.09	160	15.8	0.85	0	0	0.9125
04:00	2.09	170	16.3	0.79	0	0	0.9
05:00	2.49	180	16.8	0.75	0	0	0.9
06:00	2.49	140	16.8	0.78	48.432	0	0.8875
07:00	2.09	170	17.3	0.77	142.48	0	0.8875
08:00	2.09	140	18.4	0.78	228.24	0	0.875
09:00	3.69	90	20.1	0.67	300.744	0	0.9
10:00	4.09	110	21	0.62	355.768	0	0.9125
11:00	4.96	90	21.5	0.61	390.112	0	0.9375
12:00	3.29	100	22.3	0.57	401.792	0	0.9625
13:00	5.36	90	23.4	0.52	390.112	0	0.975
14:00	2.89	110	23.1	0.53	355.768	0	1
15:00	2.49	150	21.6	0.66	300.744	0	0.9625
16:00	3.29	100	22.5	0.56	228.24	0	0.9125
17:00	2.49	150	19	0.74	142.48	0	0.875
18:00	1.69	110	18.1	0.85	48.432	0	0.8375
19:00	2.09	170	17.9	0.85	0	0	0.7875
20:00	2.09	140	17.2	0.85	0	0	0.75
21:00	1.69	160	17.2	0.81	0	0	0.7125
22:00	2.09	140	16.9	0.82	0	0	0.6625
23:00	1.69	180	16.7	0.83	0	0	0.625

Season	Condition	Date	Initial Water Temperature (°C)
Autumn	Hot	02/03/2017	19

Time-series data

Time	Wind Speed (km/hr)	Wind Direction (°)	Air Temperature (°C)	Relative Humidity	Solar Radiation (W/m^2)	Rainfall (mm)	Cloud Coverage
00:00	2.49	60	18.7	0.79	0	0	0.4
01:00	1.69	70	17.8	0.82	0	0	0.3625
02:00	2.49	100	17.3	0.84	0	0	0.3375
03:00	2.49	80	18	0.8	0	0	0.3
04:00	1.20	90	17.7	0.8	0	0	0.2625
05:00	0.40	130	17.6	0.8	0	0	0.225
06:00	0.00	0	17	0.84	79.752	0	0.2
07:00	1.69	170	19.5	0.75	234.608	0	0.1625
08:00	1.69	110	21.3	0.68	375.84	0	0.125
09:00	1.20	80	23.4	0.58	495.224	0	0.15
10:00	2.09	150	24.9	0.51	585.832	0	0.1625
11:00	2.09	230	26.6	0.49	642.384	0	0.1875
12:00	2.09	200	27.3	0.45	661.616	0	0.2125
13:00	2.49	160	27.4	0.47	642.384	0	0.225
14:00	2.09	90	27.5	0.45	585.832	0	0.25
15:00	2.09	170	28.7	0.39	495.224	0	0.2375
16:00	2.09	190	27.9	0.42	375.84	0	0.225
17:00	2.09	190	26.3	0.47	234.608	0	0.2125
18:00	1.69	220	25.2	0.51	79.752	0	0.2
19:00	2.09	230	23.5	0.57	0	0	0.175
20:00	2.09	30	22.1	0.69	0	0	0.1625
21:00	1.69	70	20.7	0.78	0	0	0.15
22:00	1.20	60	20.4	0.81	0	0	0.1375
23:00	2.09	20	20	0.81	0	0	0.125

Season	Condition	Date	Initial Water Temperature (°C)
Autumn	Moderate	02/04/2017	19

Time-series data

Time	Wind Speed (km/hr)	Wind Direction (°)	Air Temperature (°C)	Relative Humidity	Solar Radiation (W/m^2)	Rainfall (mm)	Cloud Coverage
00:00	2.49	140	13.9	0.77	0	0	0.4375
01:00	2.09	170	14	0.72	0	0	0.425
02:00	2.89	160	13.8	0.67	0	0	0.425
03:00	2.09	170	13.3	0.67	0	0	0.4125
04:00	2.49	170	13.3	0.7	0	0	0.4125
05:00	2.09	180	13.8	0.71	0	0	0.4
06:00	2.09	160	14.3	0.66	0	0	0.4
07:00	2.09	150	16.2	0.64	70.664	0	0.3875
08:00	2.89	110	17.8	0.58	206.264	0	0.3875
09:00	4.56	110	19.2	0.53	325.152	0	0.375
10:00	3.29	110	20.6	0.53	417.696	0	0.4625
11:00	2.89	130	20.3	0.54	476.408	0	0.5375
12:00	2.89	170	21	0.56	496.52	0	0.625
13:00	3.69	110	21.8	0.49	476.408	0	0.7125
14:00	3.69	140	21.4	0.49	417.696	0	0.7875
15:00	3.29	140	21	0.52	325.152	0	0.875
16:00	3.69	140	20.5	0.54	206.264	0	0.8375
17:00	3.69	120	18.8	0.65	70.664	0	0.7875
18:00	2.89	110	17.3	0.64	0	0	0.75
19:00	2.49	130	15.4	0.71	0	0	0.7125
20:00	2.09	150	14.9	0.73	0	0	0.6625
21:00	2.49	140	14.5	0.74	0	0	0.625
22:00	2.89	140	14.2	0.71	0	0	0.5875
23:00	2.49	140	13.4	0.74	0	0	0.5375

Season	Condition	Date	Initial Water Temperature (°C)
Autumn	Cool	28/05/2017	19

Time-series data

Time	Wind Speed (km/hr)	Wind Direction (°)	Air Temperature (°C)	Relative Humidity	Solar Radiation (W/m^2)	Rainfall (mm)	Cloud Coverage
00:00	0.00	0	9.7	0.82	0	0	0.6875
01:00	0.80	120	9.5	0.87	0	0	0.725
02:00	0.00	0	9.7	0.9	0	0	0.7625
03:00	2.09	350	10.8	0.85	0	0	0.7875
04:00	1.69	310	10.8	0.92	0	0	0.825
05:00	1.20	140	10	0.97	0	0	0.8625
06:00	1.20	180	10.7	0.95	0	0	0.9
07:00	1.69	350	11.1	0.97	25.656	0	0.925
08:00	0.40	310	11	0.97	74.888	0	0.9625
09:00	2.09	10	11.1	0.99	118.048	0	1
10:00	2.09	30	11.8	0.99	151.648	0	0.9625
11:00	3.29	360	13.3	0.96	172.96	0	0.9125
12:00	3.29	360	14.2	0.93	180.264	0	0.875
13:00	3.69	340	15.2	0.85	172.96	0	0.8375
14:00	4.09	340	16.8	0.75	151.648	0	0.7875
15:00	3.69	340	16.6	0.75	118.048	0	0.75
16:00	1.69	340	16.2	0.85	74.888	0	0.7125
17:00	2.09	310	16	0.73	25.656	0	0.6625
18:00	2.89	300	14.6	0.67	0	0	0.625
19:00	2.49	310	14.2	0.65	0	0	0.5875
20:00	2.09	310	12.1	0.73	0	0	0.5375
21:00	1.69	310	10.3	0.86	0	0	0.5
22:00	1.20	330	9.3	0.86	0	0	0.4625
23:00	0.00	0	8.4	0.96	0	0	0.4125