Pindari Dam cold water pollution mitigation through artificial destratification – monitoring network recommendations

WRL TR 2022/19, April 2023

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UNSW Water Research Laboratory

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1 Introduction

Cold water pollution in reservoirs is a complex issue caused by stratification, with a range of ecological, environmental and social impacts. Despite a recognition of cold water pollution in NSW for almost two decades, it remains an issue downstream of many large storage dams. An international literature review undertaken by the UNSW Sydney Water Research Laboratory (WRL) investigated causes and impacts of, and options for mitigating cold water pollution (Chaaya and Miller, 2022). This review highlighted artificial destratification via bubble plumes as the only mitigation option capable of addressing both cold water pollution and other water quality impacts caused by reservoir stratification. The successful application of bubble plume destratification in large storage reservoirs was found to be limited, primarily due to the significant operational costs at larger scales. As such, renewable energy and optimised operational procedures are considered a necessity for feasible artificial destratification via bubble plumes in large reservoirs.

Given the limited successful application of bubble plume destratification in large reservoirs, especially in NSW, a pilot trial destratification system would be necessary to demonstrate feasibility. WRL was previously engaged by the NSW Department of Primary Industry – Fisheries (DPI Fisheries) to investigate and recommend a NSW dam at which to undertake these destratification trials. Pindari Dam located on the Severn River (Figure 1-1), one of eight high-priority dams outlined as part of the previous cold water pollution mitigating works in NSW (NSW Cold Water Pollution Interagency Group, 2012), was deemed the most appropriate.

An additional report has reviewed the data and literature pertaining to cold water pollution at Pindari Dam for DPI Fisheries (Chaaya and Miller, 2023). This provides a preliminary system design that is based on limited available data and identifies gaps in current monitoring. These gaps should be addressed prior to the commissioning of a fully operational destratification system at Pindari Dam. Specific monitoring will be required to assess key short-term (hours to days) and long-term (weeks to months) effects of artificial destratification on cold water pollution and other water quality parameters, as well as facilitate the ongoing refinement of operational procedures.

WRL was engaged by DPI Fisheries to provide options and recommendations for the design of key components for the Pindari Dam bubble plume artificial destratification trials, including:

- Monitoring – to fill the previously identified gaps in monitoring (this report)
- Operational procedures and power refinement – working collaboratively with external consultants to refine operational procedures to make effective use of renewables
- Pneumatics – investigating pipeline and diffuser design to maximise system efficiency
- Compressor design – recommendations on specific compressors based on airflow rate requirements

This report discusses the monitoring component of the engagement. It identifies the necessary datatypes to be monitored for assessing the effects of natural stratification and artificial destratification on the Pindari reservoir system. The report also highlights ongoing monitoring and whether the quality and frequency of data being collected is sufficient for design and assessment of the destratification system. Where data is deemed to be insufficient, options for monitoring instrumentation and infrastructure are provided, including estimated capital and ongoing costs based on recommendations.

Note that these costs may be subject to change based on chosen manufacturers, materials and labour costs. Additional consultation with manufacturers and suppliers will be required following the endorsement by stakeholders responsible for the purchase, operation and maintenance of instrumentation.

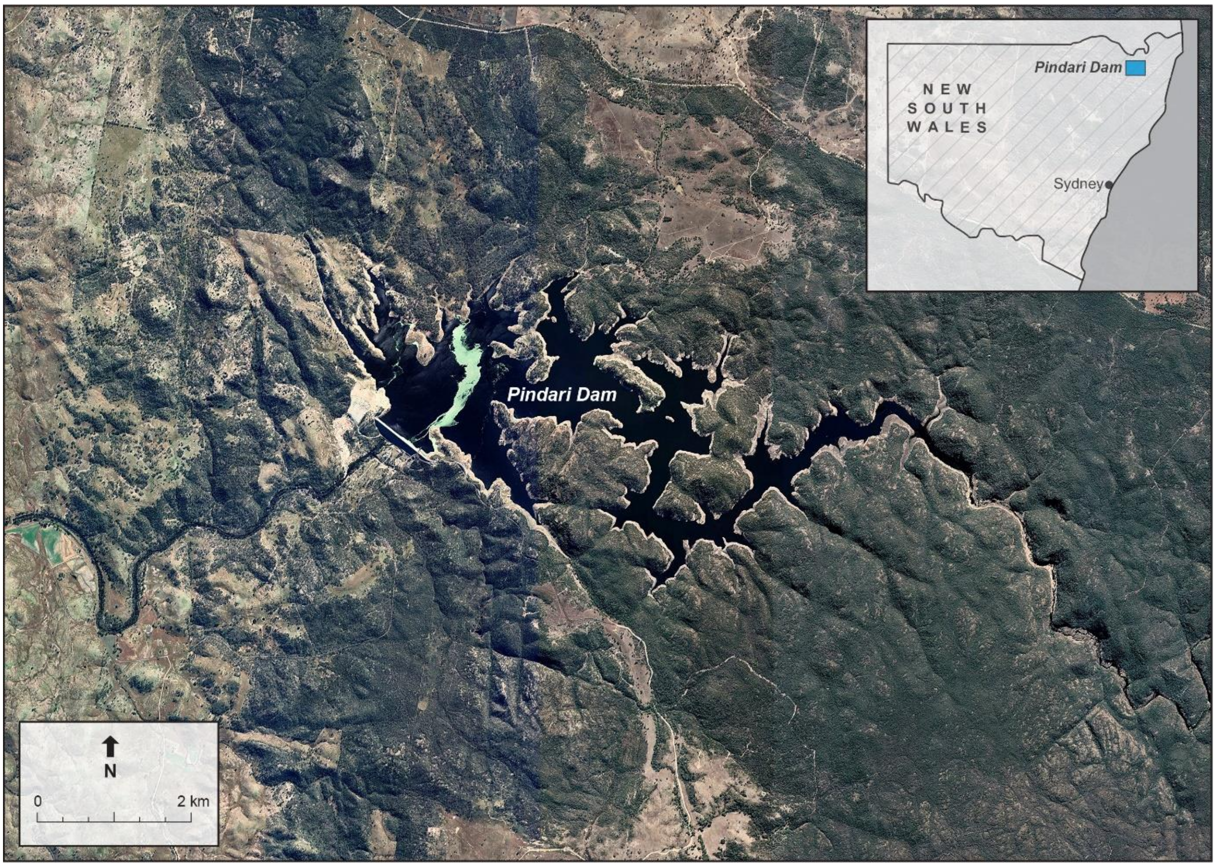

Figure 1-1 Pindari Dam location

2 Need for data

One of the current limitations of the design and optimisation of a trial destratification system for Pindari Dam is a lack of consistent and high-frequency monitoring for data types associated with stratification (and inherently cold water pollution). This data is required to conceptually and numerically model the complex hydrological and meteorological processes that effect reservoir stratification (Figure 2-1). Ongoing monitoring will be key to assessing the short- and long-term effects of an operational artificial destratification system in the reservoir. Specific data (i.e. reservoir bathymetry) will be key to mitigating the risks of damage to the submerged components of the destratification system.

WRL has identified a number of key upstream, downstream, in-reservoir and meteorological data types that are necessary to obtain and monitor to understand reservoir stratification, artificial destratification and the ongoing effects of an operational artificial destratification system. Appendix A provides a discussion on each of these data types, including their role in the reservoir system and specific use in terms of building a conceptual and numerical model of a reservoir, as well as the design processes for which they are used.

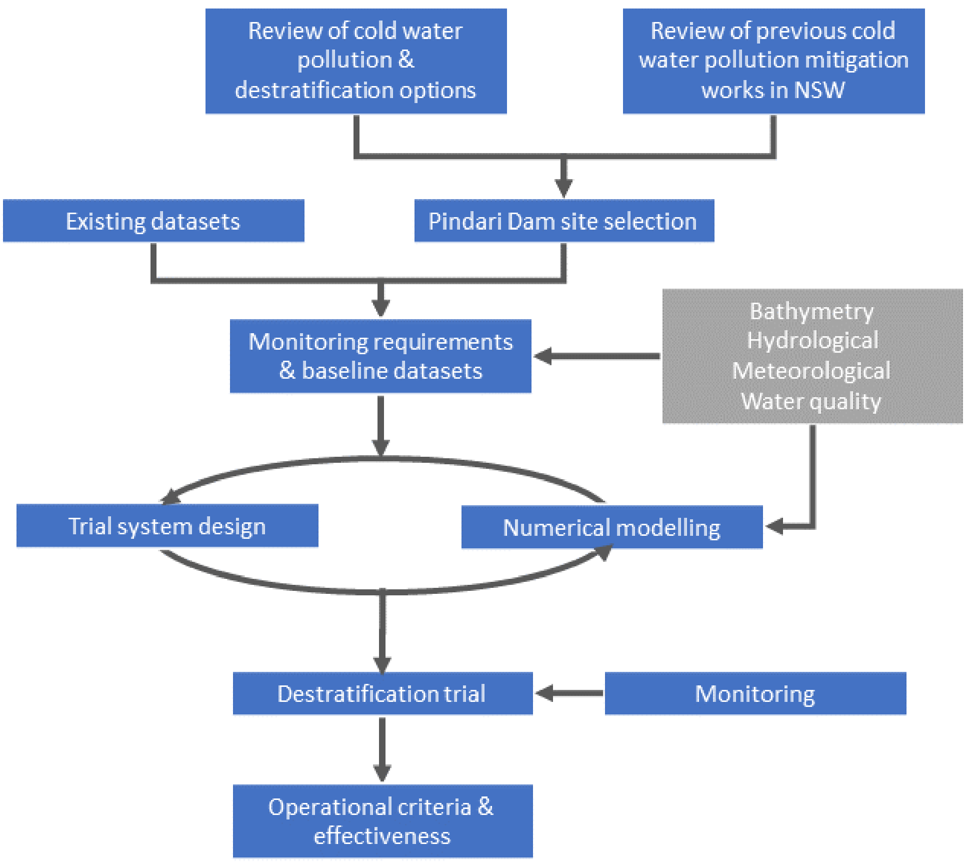

Figure 2-1 Pindari destratification trial project overview

Table 2-1 Summary of necessary datatypes to monitor prior to and throughout the Pindari Dam destratification trials

Data type	Specific parameters	Existing monitoring/data	Proposed additional monitoring
Bathymetry	n/a	DEM	Detailed bathymetric surveys
Hydrological	Inflow and outflow	WaterNSW loggers (Section 3.2.1)	None
	Up and downstream temperature	WaterNSW loggers (Section 3.2.1)	None
	In-reservoir temperature	None	Telemetered, automatic vertical profiling system Manual profiling
	Stage-storage	WaterNSW monitoring (Section 3.2.1)	None
Meteorological	Wind speed and direction	BOM weather stations (Section 3.3.1)	Establish a new automatic weather station near the dam surface
	Air temperature		
	Solar radiation		
	Rainfall		
	Relative humidity		
	Atmospheric pressure		
Water quality	Dissolved oxygen	None	Primary monitoring through regular sampling upstream, downstream and in-reservoir Supplementary monitoring through a telemetered, automatic vertical profiling system
	Nutrients	None	
	Soluble metals	None	
	Blue-green algae	WaterNSW sampling (Section 3.4.1)	

A number of the identified key data types outlined in the table above are currently monitored at a sufficient accuracy and frequency to conceptually and numerically model the Pindari system, and monitor the ongoing effects of an operational artificial destratification system. These include:

- Flows – both upstream inflows and downstream discharges, currently monitored by WaterNSW
- Temperature – both upstream inflow and downstream discharge temperatures, currently monitored by WaterNSW

- Reservoir stage-storage – currently monitored by WaterNSW

A number of the identified key data types are either not monitored, or not monitored at a sufficient accuracy or frequency. WRL has proposed monitoring solutions for these, including:

- In-reservoir temperature – depth profiling to investigate short- and long-term changes to the thermal structure in the reservoir as a result of natural stratification and artificial destratification.
- Reservoir bathymetry – undertaking a detailed whole-reservoir bathymetric survey to facilitate detailed modelling and design of the submerged component of the monitoring and destratification systems.
- Meteorological – automatic weather station monitoring to investigate the effects of specific meteorological conditions identified as the primary drivers of natural stratification and mixing in reservoirs.
- Water quality – depth profiling to monitor the short- and long-term changes to a variety of water quality parameters which are significantly impacted by natural stratification.

3 Proposed monitoring program

The following outlines the proposed monitoring program for Pindari Dam prior to and during the operation of the trial artificial destratification system. Where available data is deemed insufficient for ongoing monitoring and design, recommendations are provided regarding the type, manufacturers and potential locations for additional instrumentation.

Recommendations made throughout this report are based on previous experience with monitoring techniques, desktop investigations and a technical knowledge of reservoir stratification and artificial destratification. These should be supplemented with preliminary field investigations (undertaken by WRL engineers) prior to the purchase, installation and commissioning of the additional proposed instrumentation. These preliminary field investigations would aim to:

- Gain a greater understanding of the Pindari Dam site to aid the design of the practical components of the monitoring program (e.g. installation locations of instrumentation) and confirm the overall monitoring program design.
- Undertake preliminary data collection (primarily in-reservoir temperature profiles) to support ongoing design and modelling.

3.1 Bathymetric data

Existing detailed bathymetric survey data of Pindari Dam are unsighted by WRL or do not exist. The best current representation of the Pindari reservoir bathymetry is available through a 50 m resolution digital elevation model (DEM). This data is not of sufficient detail for the undertaking of any detailed design or modelling of the components for the trial artificial destratification system. WRL therefore recommends that bathymetric survey of the whole reservoir system be obtained to support:

- Design of the submerged component of the destratification system
- Design of the in-reservoir monitoring locations
- Detailed numerical modelling

Appendix A1 provides a detailed discussion on the use bathymetric surveys and methods for obtaining surveys. In short, it is recommended that a multibeam survey be undertaken in the area in which the diffuser pipeline is to be installed (the reservoir thalweg) to reveal any significant obstructions that may cause issues when sinking or raising the diffuser. Single beam surveys will be sufficient for the remaining reservoir extent. This will be used for conceptual and numerical modelling of the reservoir, which does not require the precision provided by the multibeam surveys. Figure 3-1 below indicates the recommended extent of the multi and single beam surveys, based on the estimated indicative placement of the diffuser along the reservoir thalweg (as seen in the current DEM).

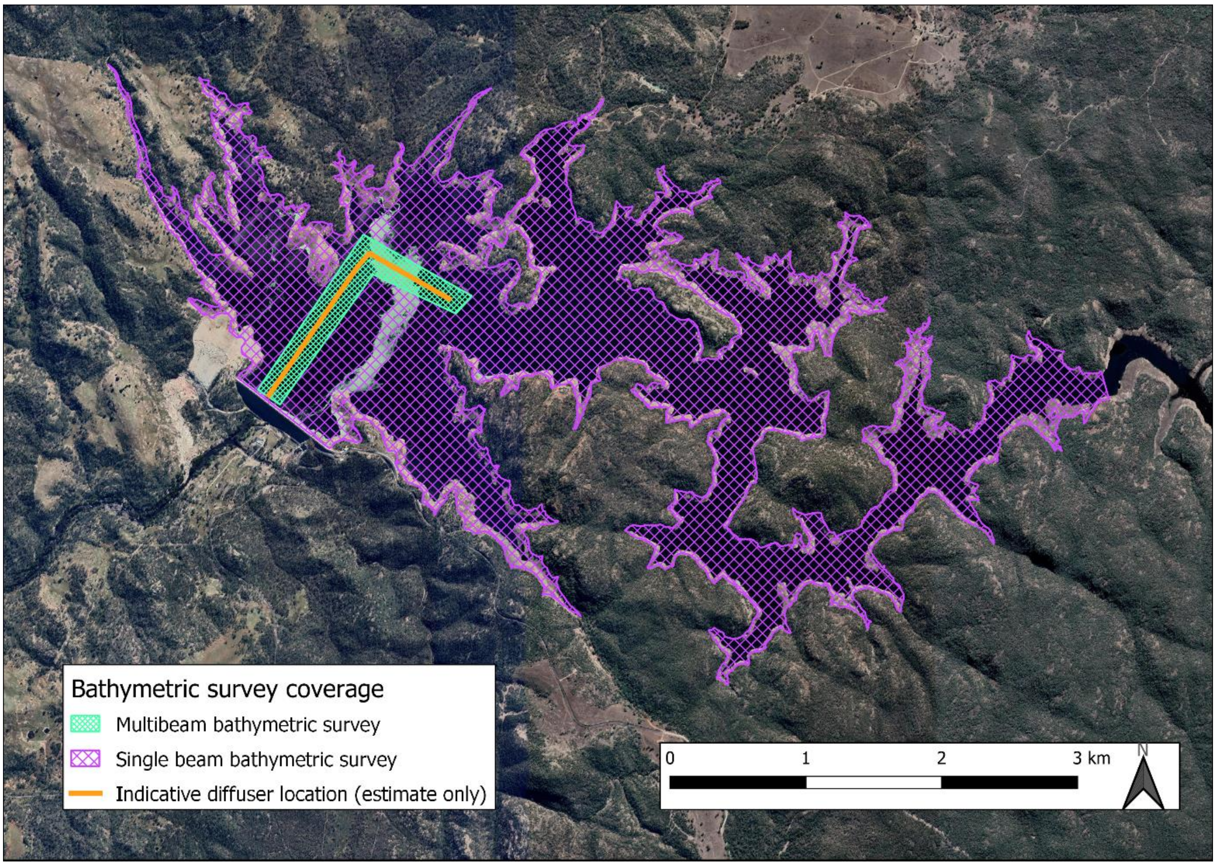

Figure 3-1 Recommended bathymetric survey extent

Should existing detailed bathymetric surveys of Pindari be available, and depending on their resolution, additional single beam surveys may be unnecessary. At a minimum, multibeam bathymetric surveys should be undertaken as soon as possible, to facilitate the ongoing design of the submerged components of the destratification system.

3.2 Hydrological

3.2.1 Current monitoring

WaterNSW currently monitors several necessary hydrological parameters upstream (inflow), downstream (discharge) and in-reservoir at Pindari Dam (Figure 3-2). This data is made available through their real-time data service, and includes:

- Upstream flow and temperature – Severn Gauge at Strathbogie [416039]
- Downstream flow and temperature – Severn Gauge at Ducca Marri [416067]
- Reservoir stage-storage (i.e. water level and volume), net inflows and release volumes – Pindari Dam Gauge [416030]

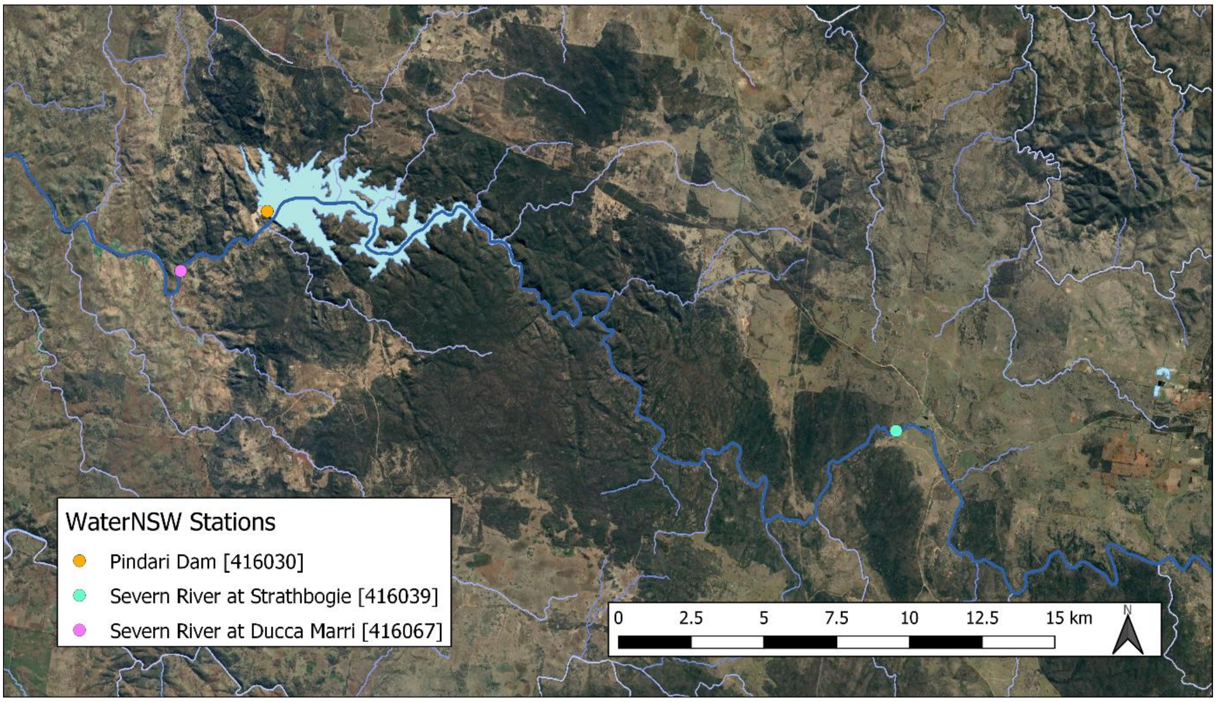

Figure 3-2 Location of WaterNSW hydrological monitoring stations upstream, downstream and in Pindari reservoir. Reservoir (light blue) and Severn River watercourse (dark blue) pictured.

The frequency at which this data is collected is considered sufficient for monitoring purposes throughout the artificial destratification trial. Preliminary analysis of this data (i.e. the water balance of the reservoir system) has highlighted discrepancies between the inputs (upstream inflows and rainfall), outputs (downstream flows and evaporation) and changes to storage volumes. Additional information from WaterNSW regarding the instrumentation and monitoring methodology should be requested to validate the data currently being recorded.

3.2.2 Proposed additional monitoring – automated in-reservoir temperature profiling

WRL is unaware of any current in-reservoir temperature monitoring conducted at Pindari Dam. In-reservoir temperatures are necessary to monitor the short-term and long-term effects of the trial destratification system. WRL recommends long-term (i.e. over the trial duration) automated and telemetered temperature profiling in at least two locations in the reservoir during the destratification trials (see Figure 3-4 for potential locations):

- In the vicinity of the offtake tower – to capture the effect of artificial destratification in the section of the reservoir from which water is withdrawn for release
- Upstream of the bubble plume diffuser – to capture the effect of artificial destratification away from the near-field influence of the bubble plume

It is not necessary to establish profiling at these locations immediately. It is sufficient to establish profiling in a single location for preliminary investigations during the summer period before the trial commences to establish baseline conditions. WRL recommends, should this option be pursued, that profiling be conducted in the deepest section of the reservoir. This instrumentation could then be repositioned to one of the two aforementioned long-term profiling locations with the purchase of additional profiling instrumentation to fulfill the proposed minimum monitoring requirements for the destratification trail.

WRL has identified two options for temperature profile monitoring at Pindari:

- Vertical profiling system (VPS)
- Thermistor string

While both options appear economically and functionally feasible for Pindari, communications with dam managers have indicated that thermistor strings will be difficult to manage in a reservoir as deep as Pindari. This is primarily due to the risk of entanglement with obstructions at the bed or the mooring system with lowering water levels, resulting in damage or loss of equipment with proceeding water level increases. The VPS has specifically been recommended as a safer alternative due to its ability to adjust profiling depths based on location and water levels.

Automatic vertical profiling system

A YSI VPS (supplied by Xylem) uses an automated winch system to periodically raise and lower a YSI EXO2 multi parameter sonde through predetermined depths in the water column to measure temperature and a number of water quality parameters through an array of sensors. The modular, automated system offers the following advantages:

- The ability to monitor other water quality parameters through depth profiles, in addition to temperature monitoring.
- The modular sensor array (up to seven sensor) allows additional parameters to be incorporated into the monitoring program at a later date, if deemed necessary.
- Manufacturers offer out-of-the-box telemetry and dashboard integration.
- The system is capable of detecting water depth and the location of the bed of the reservoir. This can alleviate the risk of instrumentation being caught on a snag at the bed of the reservoir.
- Re-deployable within Pindari or at another site post-trial.

Disadvantages of using a VPS system include:

- A VPS is potentially a high-cost solution compared to a simple thermistor string.
- Failure of the winching system will cease all valuable monitoring.
- Higher maintenance solution compared to a simple thermistor string.
- Frequency of profiling limited by depth locations and stabilisation period. At Pindari's maximum depth, a full cycle may be upwards of 3 hours.

Product developers Xylem offer both a fixed and buoy mounted system. A fixed system, likely mounted on the dam wall, offers the advantage of accessibility with the disadvantage of limited choice of profiling location. A buoy mounted system can be moored anywhere in the reservoir, offering the advantage of profiling in a key location other than the dam wall with the disadvantage of more complicated access and higher cost.

It will be necessary to include at least one VPS system as part of the monitoring instrumentation if automated, telemetered water quality monitoring is required.

WRL recommends profiling at the highest frequency capable, which will be dependent on the depth of the reservoir in which monitoring occurs. Xylem (per comms.) have suggested allowing 1 minute per depth interval, to allow the probe to stabilise in the water column. WRL recommends logging at 1 m intervals through the full water column. Optimisation of the programming would be determined during the pre-trial data collection phase.

Thermistor strings

WRL does not recommend the use of thermistor strings in the deep sections of the reservoir, based on limitations highlighted by current dam managers (see disadvantages listed below). This option should only be considered in an expanded automated network in the shallower parts of the reservoir, due to the cheaper instrumentation costs compared to a VPS. This expanded monitoring can be undertaken through targeted manual profiling (as discussed in Section 3.2.3).

Thermistor strings offer a lower maintenance, lower cost solution to collecting temperature depth profile data. These are generally buoy mounted or attached to the dam wall. Thermistor strings offer the following advantages:

- Higher frequency of data collection as they are not limited by the use of a single sensor.
- For the purposes of temperature profiling alone, thermistor strings are a cheaper solution than a VPS and thus offer a more expandable solution.
- Lower maintenance costs.
- Re-deployable within Pindari or at another site post-trial.

The disadvantages of using thermistor strings include:

- Unable to monitor any other water quality parameters.
- Depending on the mooring system, there may be issues with tangling mooring lines and the thermistor string. This may result in damaged equipment.
- Potential issues with snagging at the bottom of the reservoir at lower levels limiting the ability of the buoy to re-raise with increasing water levels. This may result in lost or damaged equipment.
- Inaccessibility with buoy mounting or at lower water levels in deep storages when attached to the dam wall.

3.2.3 Proposed additional monitoring – targeted, manual temperature profiling

WRL recommends additional manual temperature profiling should be undertaken at additional locations away from the two automated profiling locations proposed. These sites would inform a greater understanding of the effects of artificial destratification in the branching sections and upper reaches of the reservoir. The geometry of Pindari, especially the arms off the main thalweg of the reservoir, may result in complex destratification effects. While this may not specifically affect the capability of the destratification system in mitigating cold water pollution, there is the potential for insufficient mixing in these sections that may facilitate blue-green algae growth or other water quality concerns. Profiling in these locations would assist with an understanding of these effects during the trial period, should they be present.

This additional manual monitoring would be specifically targeted at key events, including:

- Pre- or post-onset of natural stratification to complement the numerical and conceptual understanding of the system.
- Annual summer stratification period prior to the operation of the destratification system).
- Degradation of water quality (e.g. dissolved oxygen (DO) stratification or a blue-green algae bloom event) during operation of the destratification system to understand cause and effects at a whole-reservoir scale.

Initial temperature profiling would be undertaken by WRL as part of field investigations through the summer period prior to the commencement of the trial. Ongoing manual temperature profiling monitoring may be combined with the concurrent water quality monitoring (see Section 3.4.2) if this would involve in-reservoir sampling.

3.3 Meteorological

3.3.1 Existing weather stations

There are three Bureau of Meteorology (BOM) weather stations within the vicinity of Pindari Dam that collect data relevant to modelling stratification (Figure 3-3). These are:

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

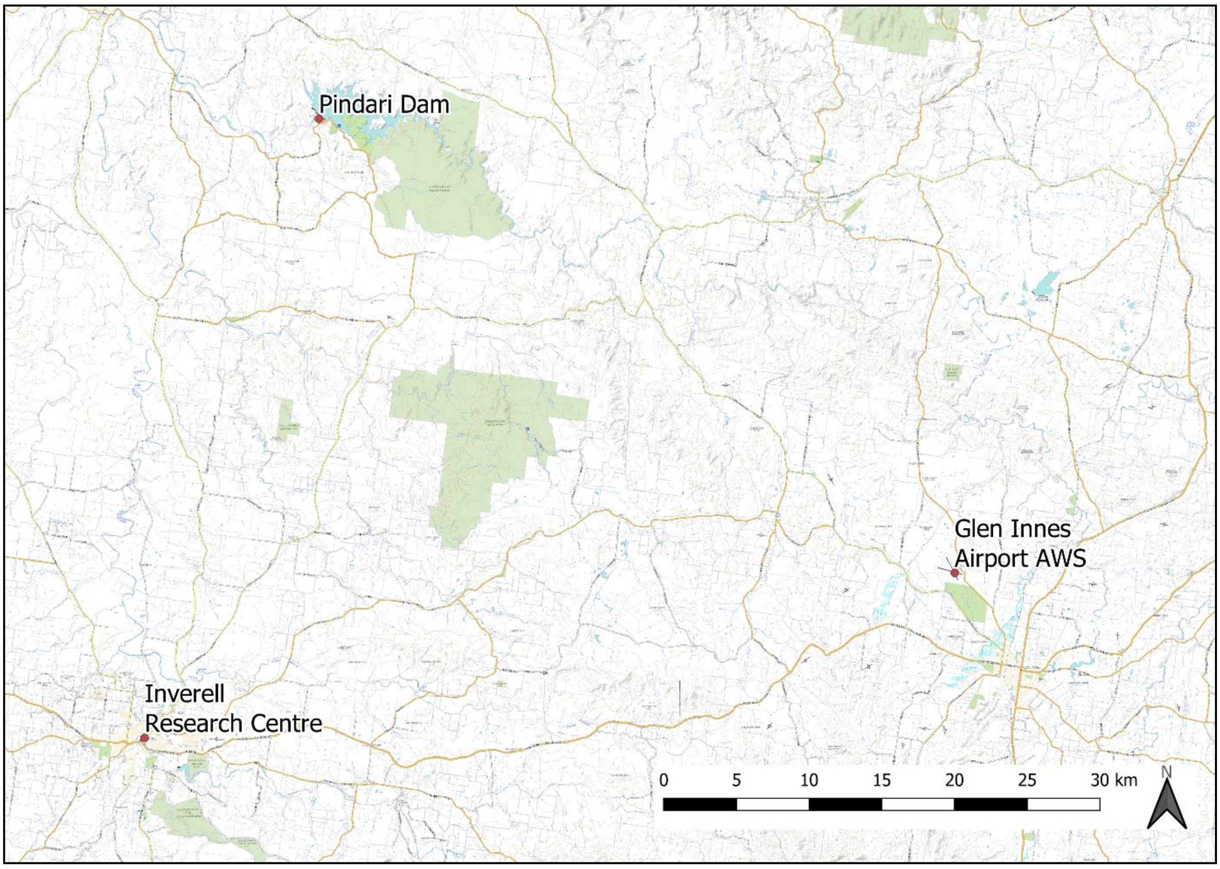

Figure 3-3 BOM station locations

Data from the Pindari Dam station is considered most representative of the conditions at the surface of the reservoir. Unfortunately, data is only collected at a daily frequency of approximately 5 days a week. This frequency of collection is not sufficient to monitor meteorologically influenced changes to stratification in Pindari.

Data from the Inverell Research Centre and Glen Innes Airport stations collect data at a higher frequency than the Pindari Dam station, however they are located 45.5 and 54 km respectively from Pindari Dam. The variation in surrounding topology and elevation at these stations, compared to Pindari, makes them unreliable in terms of representing the conditions that affect the reservoir surface. Quantitative analysis comparing the data recorded at both stations and Pindari highlights this unreliability.

It will be necessary to establish a new local automatic weather station at Pindari Dam for the upcoming destratification trials that monitors sub-diurnal meteorological conditions.

3.3.2 Proposed additional monitoring – local automatic weather station

Establishment of an automatic weather station (AWS) at Pindari Dam is recommended. The AWS should be set up as close to the reservoir surface as possible. Ideally, the station would be situated on a pontoon or buoy which is raised and lowered with the changing reservoir water levels. This would provide the best representation of meteorological conditions affecting the reservoir surface. However, for long-term measurements, having the pontoon rise and fall with the dam water levels may provide unrepresentative long-term data.

A land-based station will not provide conditions perfectly representative of those at the reservoir surface, however there will be more certainty in the stability of the data provided. Consideration should be given to potential obstructions (e.g. infrastructure, topography, trees, etc.) affecting the representation of data from one or more directions.

Based on this, it is recommended that the AWS be mounted on the dam wall. This would allow unobstructed exposure to conditions from every direction and provide an acceptable representation of the conditions at the reservoir surface. However, depending upon local installation issues, if a dam wall mounted solution is not a feasible option, a bank- or pontoon-mounted station will be acceptable. The abovementioned disadvantages of these alternative solutions should be considered in their selection.

Installation of the AWS should consider security and limiting public access to ensure safety and mitigate vandalism. Access for maintenance should be considered. Field investigations undertaken by WRL would assist with establishing the most appropriate location, in consultation with key staff from WaterNSW and the chosen AWS supplier (see Figure 3-4 for potential locations).

There are two options available, depending on the manufacturer of choice:

- All-in-one
- Multi-sensor configuration

All-in-one systems are generally cheaper and easier to deploy, however maintenance and repair can be more complicated due to the interconnection of all the instrumentation in the one housing. If one instrument fails, the whole station may need to be decommissioned temporarily to undertake repairs. While multi-sensor configurations are generally more expensive, in the instance of instrument failure, they have the advantage of separate sensors being easier to replace or repair without interrupting other data collection. Individual sensors as part of a multi-sensor configuration generally collect data to a greater degree of accuracy.

Potential suppliers for the AWS include:

- Campbell Scientific
- Environdata
- ICT International
- Xylem

WRL recommends sampling meteorological parameters at a frequency of 15 minutes. The AWS should ideally be established through the summer period prior to the commencement of the trial .

3.4 Water quality

3.4.1 Current blue-green algae monitoring

Blue-green algae monitoring is currently conducted routinely from three locations around Pindari Dam, including the dam wall, boat ramp and upstream inflow (NSW Department of Planning Industry and Environment, 2020). This data is collected to inform alerts based on National Health and Medical Research Council guidelines (NHMRC, 2008). These alerts indicate health risks due to the presence of toxic blue-green algae.

WRL has not sighted this data at the time of writing. Historical records of this monitoring program would assist with the investigation into the effectiveness of current cold water pollution mitigation strategies through selective withdrawal at Pindari. The data obtained from this monitoring is likely insufficient for assessing the ongoing effects of artificial destratification on blue-green algae growth. NHMRC (2008) indicate methods of sampling at the surface, as this monitoring is focussed on impacts to human health.

Therefore, additional monitoring of blue-green algae concentrations will be required, including the change in predominating algal species through the entire water column as part of the destratification trials at Pindari Dam. The results of this monitoring will be used to investigate:

- Whether artificial destratification is successful in reducing blue-green algae growth
- How artificial destratification affects the distribution of blue-green algae concentrations other predominating algal species through the water column
- Whether a redistribution of blue-green and predominating species of algae through the water column results in a significant increase in concentration downstream
- The corresponding change in the species of algae in an aerated storage and the potential risks that predominating species may pose to human health and/or the environment

3.4.2 Proposed additional monitoring – water quality manual sampling and automated profiling

WRL understands that a contractor has been engaged to undertake water quality monitoring as part of the Pindari Dam monitoring program. Although the specific design of this water quality monitoring program is unknown to WRL at this stage, it is understood that sampling and laboratory testing will be used to assess a number of water quality parameters. This sampling will investigate those water quality parameters outlined in Table 2-1 and Appendix A4 as necessary to monitor in order to gain an understanding of the impacts of natural stratification and the potential benefits or drawbacks of artificial destratification.

Sampling will occur routinely at weekly to monthly intervals, with an increase in frequency triggered by the increase in concentration or counts of specific parameters. It will be beneficial to sample through the water column, or at a minimum at the bed and surface of the reservoir. This will provide water quality data that can be compared to the data collected through automated vertical profiling.

Routine, manual sampling provides the opportunity to target specific locations and events. Sample collection and laboratory analysis provides a more direct and accurate measure of water quality parameters which are complicated or impossible to monitor through automated sensors in the field, including nutrient, soluble metals and blue-green algae concentrations. This type of monitoring will be necessary for quantifying detailed changes to the water quality as a result of stratification and artificial destratification. Data collected through manual sampling will inform a more detailed understanding of the short-term changes to water quality observed through automated profiling. For this reason, WRL recommends manual water quality sampling be undertaken near automated VPS systems established in the reservoir.

Automated and telemetered profiling will supplement the ongoing manual sampling as part of the monitoring program. The YSI VPS (supplied by Xylem), with specific sensors included in the EXO2 multi parameter sonde, is able to profile monitor a number of water quality parameters in tandem with temperature monitoring. Data collected from sensors measuring nutrient and blue-green algae concentrations is not as reliable as that collected through manual sampling and laboratory testing. The EXO2 sensors, however, perform well when collecting dissolved oxygen and pH data.

This type of continuous and higher frequency water quality monitoring may indicate short-term changes to water quality that will better support the understanding of the application of destratification systems in large dams and optimising their operation.

The data collected through the automated VPS and manually sampled monitoring can be used in conjunction to gain a greater understanding of the water quality processes in Pindari reservoir. Additionally, the VPS continuous monitoring may act as an early warning system for significant changes to the water quality which trigger increased manual sampling frequency.

There are limitations to consider with water quality monitoring through a VPS:

- Profiling in a fixed location may not facilitate a holistic understanding of the short-term effects of stratification on water quality in the wider reservoir.
- A number of key water quality parameters cannot be monitored through the sensors available for the VPS, including iron and phosphorus.
- Concentration of nitrogen and blue-green algae are not measured directly, and instead detected through surrogates to their presence (i.e. chlorophyll-a).
- Manganese is not directly measurable. Instead, manganese concentration can be potentially determined using oxidation reduction potential (ORP), DO and pH measurements (Bertone et al., 2015). This would require other local field data to confirm the relationship as applicable to Pindari reservoir.
- In terms of key water quality parameters related to stratification and artificial destratification, temperature and DO are the only parameters that can be reliably monitored through a VPS sensor.

Additional sensors for this monitoring will cost approximately 15 - 20% of the total instrumentation cost for the VPS. This monitoring would be conducted at the same frequency and resolution as the concurrent temperature profiling.

Sensors that can be used to monitor additional water quality parameters include:

- Optical DO sensor – dissolved oxygen monitoring.
- ORP sensor – oxidation reduction potential sampling of redox-active species (soluble metals).
- pH sensor – surrogate measurement for manganese concentrations and generally representative of water quality. Literature suggests that lowering pH can facilitate a shift from blue-green algae dominance to more favourable species (Chaaya and Miller, 2022), the observation of which pH data would facilitate.
- Total algae fluorescence sensor – measures chlorophyll-a and phycocyanin (specific accessory pigment found in blue-green algae).
- NitraLED UV nitrate sensor – measures nitrate concentrations. Nitrate is a dissolved inorganic form of nitrogen known to stimulate growth of toxic cyanobacteria (Perovich et al., 2008).
- Turbidity sensor – turbidity is inherently linked to Secchi depth, which describes the depth of light penetration through a water column. As algae growth is limited by light availability, turbidity data may supplement the understanding of the growth and decay dynamics of blue-green algae and other species under artificially destratified conditions.

WRL recommends the chosen sensors be included with each VPS system established at Pindari Dam.

3.5 Potential locations for additional monitoring instrumentation and infrastructure

Potential locations for monitoring are outlined in Figure 3-4 and Table 3-1. These should be considered estimates based on desktop GIS analysis. As proposed, WRL will undertake the required field investigations in consultation with WaterNSW and DPI Fisheries to confirm the monitoring program design and specific installation locations.

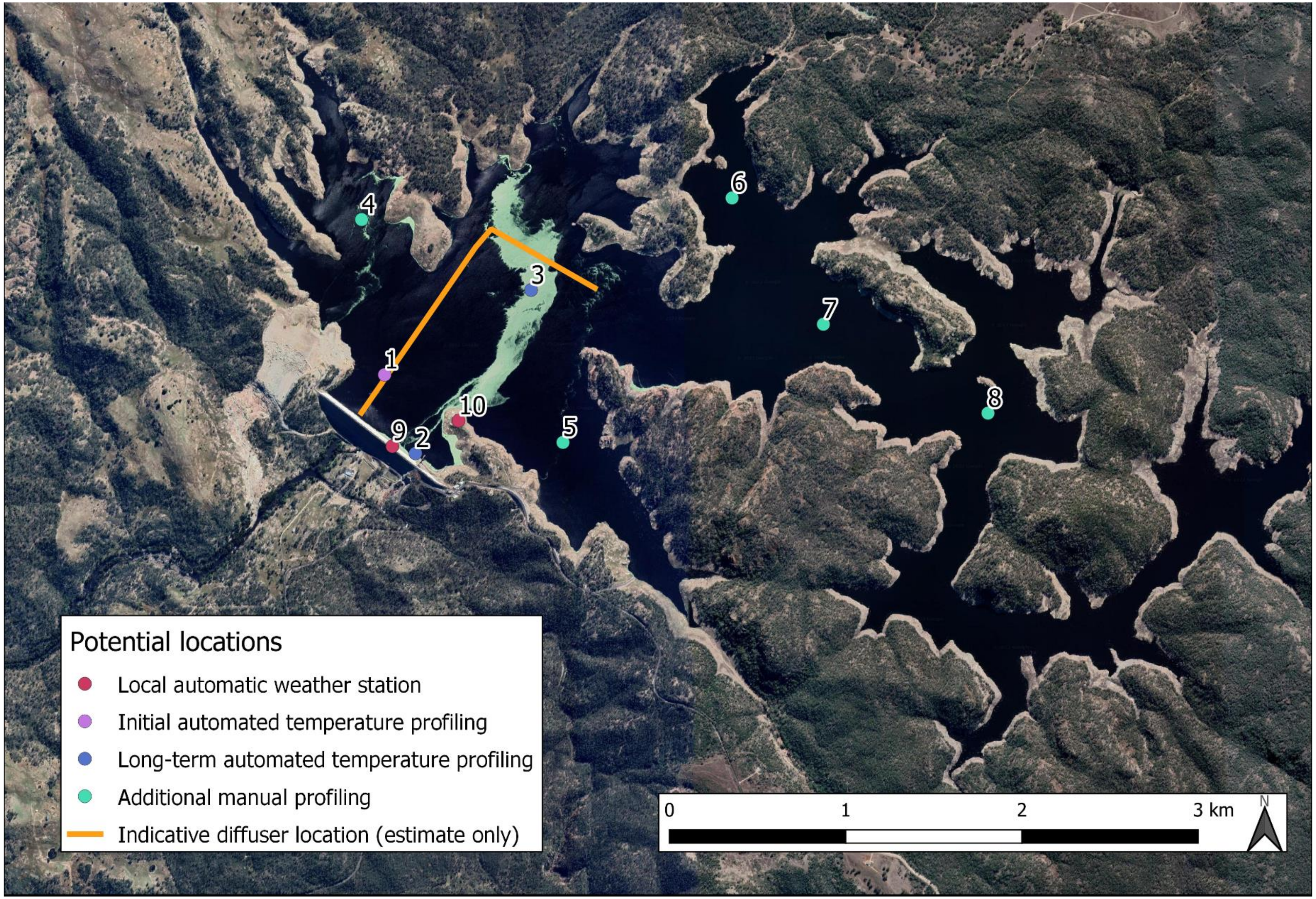

Figure 3-4 Potential meteorological and in-reservoir profiling monitoring locations for Pindari Dam (subject to field investigations)

Table 3-1 Potential monitoring locations

Monitoring type	ID	Location	Comments
Initial automated profiling (optional)	1	Deepest section of reservoir	Recommended location for initial profiling should the option to purchase a single set of profiling instrumentation be pursued (see discussion in Section 3.2.2).
Long-term automated profiling (Section 3.2.2)	2	Dam wall/offtake tower	One of two necessary temperature and water quality profiling locations. Monitoring here will inform the effect of destratification on the water column near the offtake. Need to consider: • Instrumentation location to avoid damage through offtake or spillway withdrawals • Choice of a pontoon or wall-mounted profiling system • Public access and security from vandalism • Accessibility for maintenance
Long-term automated profiling (Section 3.2.2)	3	Upstream of diffuser location	One of two necessary temperature and water quality profiling locations. Monitoring here will inform the effect of destratification upstream of the direct diffuser influence. This location will be subject to the designed length of the diffuser. Need to consider: • Public access and security (may require exclusion zone) • Choice of VPS or thermistor string • Accessibility for maintenance • Locating away from direct bubble plume near-field mixing
Additional manual temperature profiling (Section 3.2.3)	4	Branch	Potential locations for additional manual temperature profiling. These locations would be subject to analysis of detailed bathymetric surveys and a visit to the Pindari Dam site by WRL. This is not a specific recommendation on the number of locations at which manual temperature profiling should be undertaken. Monitoring at these locations would specifically target sections of the reservoir where distance from the diffuser or bathymetry might affect destratification.
	5	Branch	
	6	Branch	
	7	Upstream thalweg	
	8	Upstream thalweg	
Automatic weather station (Section 3.3.2)	9	Bank-mounted	Potential locations for the automatic weather station. Dam wall preferred due to minimal topographic obstructions. Need to consider: • Public access and security • Accessibility for maintenance • Influence of topographic obstructions if bank-mounted • Influence of the large dam wall infrastructure if dam wall-mounted
	10	Dam wall-mounted	

4 Estimated costs

Table 4-1 summarises the estimated costs of the recommended additional monitoring, instrumentation and infrastructure for the Pindari Dam artificial destratification trials. These costs should be considered an estimate only, based on preliminary quotes provided by various manufacturers. Cost changes will be subject to:

- Choice of instrumentation, manufacturer and servicing agreement
- Location of meteorological and profiling stations
- Mooring requirements for in-reservoir profiling stations, based on analysis of the detailed bathymetric surveys and site constraints
- Available telecommunications network coverage onsite (where low coverage would require additional communications solutions)

Quotes have been provided to DPI Fisheries with the submission of this report. The quotes provided will expire, and manufacturers should be contacted for updated information with the confirmation of monitoring program design.

Table 4-1 Estimated costs for additional recommended monitoring at Pindari Dam

Item	Component	Unit cost ($)	Ongoing unit cost ($/year)	Number	Indicative CAPEX ($)	Indicative OPEX ($/year)
WRL preliminary field investigation[1]	Travel and accommodation expenses	$2,000		1	**$2,000**	
	Labour (including data processing)	$20,000		1	**$20,000**	
	Boat hire (3 days)	$7,500		1	**$7,500**	
Bathymetry survey	Partial (thalweg) multibeam survey	$26,000		1	**$26,000**	
	Whole-reservoir single beam survey	$68,000 [2]		1	**$68,000**	
	Whole-reservoir multibeam survey	$132,000		0		
Vertical profiling system	Pontoon platform and winching system	$110,000		2	**$220,000**	
	Sensors	$30,000		2	**$60,000**	
	Delivery, installation and commissioning [3]	$16,000		2	**$32,000**	
	Service agreement		$18,000	2		**$36,000**
	Winch maintenance		$3,250	2		**$6,500**
	Sensor calibration and maintenance		$2,200	2		**$4,400**
Thermistor string [5]	Thermistor string	$50,500 [4]		0		
	Telemetry buoy	$22,000		0		
	Installation and commissioning	$8,300		0		
	Servicing agreement		$6,700	0		
	Logger calibration		$100	0		
Automatic weather station	AWS stand and sensor components (inc. delivery)	$16,000		1	**$16,000**	
	Installation and commissioning	$3,500		1	**$3,500**	
	Servicing agreement		$2,000	1		**$2,000**
				Total [6]	**$455,000**	**$48,900**

[1] This would include initial profiling and site investigation in consultation with key WaterNSW staff to confirm monitoring design proposed by WRL.

[2] This price would reduce depending on the cover of a partial multibeam survey, if undertaken.

[3] Manufacturer has indicated that decommissioning and removal of the system would be approximately equal to the installation and commissioning costs.

[4] This price is based on a 1 m resolution thermistor string in the deepest part of Pindari reservoir.

[5] Not recommended at this stage, based on the disadvantages highlighted in Section 3.2.2.

[6] Excludes WaterNSW asset owner operator costs (if required) such as advice, contractor and site safety management, power, site preparation/re-establishment, data handling, telecommunications and O&M activities during the trial period.

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Appendix A Data types associated with stratification and cold water pollution

A1 Bathymetric

Reservoir bathymetry is crucial for designing the size, location and anchoring method of the distribution and diffuser pipeline network as part of the artificial destratification system. A bed-anchored pipeline and diffuser is at risk of damage or ineffective installation without accurate bathymetry data. There is an inherent inaccessibility with a system installed at the bed of the reservoir. The strategic placement of the pipeline and diffuser is crucial to ensure it is at minimal risk of failure. Understanding the reservoir bathymetry is key to designing the in-reservoir monitoring network to collect valuable data, and to minimise the risk of damage to the instrumentation due to changing water levels (e.g. a thermistor string catching on trees at the bed of the reservoir or mooring configurations).

Reservoir bathymetry is a core component of the conceptual and numerical model of a reservoir. Accurate representation of the bathymetric structure of the reservoir will assist with accurately modelled stratification and destratification processes. As well as this, it is a key link between the stage-storage data of a reservoir and can be considered the most accurate way to determine storage volume based on stage (i.e. water level) data.

Bathymetric surveys are collected through single beam (low-resolution) or multi beam (high-resolution) echo sounding instrumentation. Multi beam echo sound surveys should be, at a minimum, undertaken along the thalweg. This will reveal any significant obstructions that may cause issues for the installation and recovery of the submerged components of the destratification system. Reservoir-wide bathymetry can be collected using single beam echo sounding. This will be used as an input to the numerical model, and does not require the same resolution and detail that is obtained through multi beam surveys.

Bathymetric data is used for:

- Relating stage-storage data
- Design of the pneumatic piping network for the artificial destratification system
- Design of the in-reservoir monitoring network
- Conceptual and detailed numerical modelling

A2 Hydrological

A2.1 Temperature

Temperature data is the single most important data type to be monitored for the purposes of investigating cold water pollution, stratification and the effects of artificial destratification. Temperature profiles, in particular, show the thermal structure of the reservoir through the water column which is a key indication of the presence of stratification, or lack thereof as a result of artificial destratification. Temperature profile data should be collected from at least two different locations in a larger reservoir:

- In the vicinity of the offtake tower, to demonstrate the effectiveness of the destratification system for mitigating cold water pollution downstream.
- Away from the immediate diffuser location, to assess any potential limitations the destratification system has in destratifying the whole reservoir.

In terms of a general and conceptual understanding of the reservoir system, temperature profiling is used for:

- Conceptual understanding of the stratification and natural mixing processes
- Relating changes in meteorological conditions to changes in stratification
- Relating in-flow mixing mechanisms to changes in stratification
- Initialisation, calibration and verification of a detailed numerical model

In terms of specifically investigating the water column thermal structure pre- and post- artificial destratification, temperature profiling is used for:

- Observing the depth of the thermocline
- Observing the strength of stratification (i.e. difference between the temperature above and below the thermocline)
- Observing key changes to the state of stratification in a reservoir due to natural meteorological and hydrological effects
- Observing key changes to stratification as a result of various artificial destratification operations
- A key feedback parameter to optimise the variable flowrate of an artificial destratification system

Downstream temperature data is the key indicator of cold water pollution. While stratification occurs within the reservoir itself, cold water pollution affects river systems downstream of the dam. Monitoring temperature in one or more locations downstream of a dam is crucial for:

- Quantifying the extent of the effects of cold water pollution downstream
- Quantifying the effects of artificial destratification on cold water pollution downstream
- Quantifying the ecological benefits of artificial destratification and measuring the nature of its success
- Calibrating and verifying a detailed numerical model of the dam

Upstream temperature data contributes to an understanding of the mixing effects of incoming flows to the reservoir system. Colder inflows entering the existing upper stratified layer will plunge below the thermocline. Warmer inflows entering the existing upper stratified layer will propagate into the reservoir in the surface layer. Upstream temperature data is used for:

- Conceptual analysis of the natural mixing introduced by inflows
- Temporally varying input into the dam numerical model

A2.2 Flow

Upstream inflows contribute a significant proportion of the water coming into the reservoir system, compared to other mechanisms such as direct rainfall (discussed in Section A3.4) and catchment run off (which, in part, directly contributes to upstream flows). Inflows, in particular upstream river inflows, provide a natural mixing mechanism for a stratified reservoir. The magnitude of the flow is proportional to the mixing energy contributed. Upstream flow data is used for:

- Conceptual analysis of the natural mixing introduced by inflows
- Temporally varying input into a reservoir numerical model
- Verifying the conceptual and numerical water balance in a reservoir system

Outflow from a dam is the primary contributor to cold water pollution downstream. The magnitude and extent of the impacts of cold water pollution increase with increasing outflows (release volumes). Water can be released from dams via a number of mechanics including multi-level offtake withdrawal, deep offtake withdrawal or spillway flows. Downstream flow data is used for:

- Conceptual understanding of the contribution of flow volume to changes in downstream thermal regime
- Temporally varying input in a reservoir numerical model
- Verifying the conceptual and numerical water balance in a reservoir system

A2.3 Reservoir stage-storage relationship

The reservoir stage-storage relationship relates the stage (water level) to the storage (volume) within a reservoir. Both stage and storage information are a key component of the water balance of the reservoir system. The stage-storage relationship provides a conceptual and numerical understanding of the general shape of the reservoir. Stage data is used for:

- Verifying the conceptual and numerical water balance of the system
- Numerical model verification, calibration and temporally varying model inputs
- Monitoring and modelling overtopping events (i.e. spillway flows)
- Monitoring changes to reservoir water levels that may affect in-reservoir profiling monitoring
- Stage-storage relationship

Storage data is used for:

- Verifying the conceptual and numerical water balance of the system
- Stage-storage relationship

A3 Meteorological

A number of meteorological conditions play a key role in the natural stratification and mixing of a reservoir system. While these conditions are relatively simple to monitor individually, their interplay at the surface of the reservoir is complicated. This can make it difficult to quantify and relate their influence on reservoir stratification and mixing. On a basic conceptual level, this data can be used to investigate general meteorological trends and their relationship to long-term changes to the thermal state of the reservoir water column. Higher-level detailed numerical analysis and modelling is required to relate changes in these conditions to thermodynamic changes in the reservoir system over a shorter period (hourly to daily).

These conditions represent a key input into the reservoir numerical model as they are the primary drivers of the surface heat exchange and mixing in the reservoir system. Accurate representation of the conditions at the surface of the reservoir is necessary for a detailed conceptual and numerical understanding of their influence on stratification. Meteorological conditions should be monitored from a location close to the surface, considering potential obstructions to clear measurements such as topography and infrastructure.

A3.1 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. Monitoring of both wind speed and direction as close to the surface of the reservoir is key to representing the conditions that affect the surface directly. Wind speed contributes to evaporation at the surface of the reservoir. Accurately represented data from the reservoir surface will assist with refined investigations into evaporative water loss savings. The predominance of wind direction and its speed may provide intelligence as to the potential risks for the accumulation of blue-green algal biomass near a dam offtake.

A3.2 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 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, qualitative 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.

At a shorter timescale (less than daily), 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 and adjusting the diurnal operational range of the compressors for bubble plume destratification system to minimise energy costs).

A3.3 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.

Like air temperature, solar radiation can be linked for both diurnal and seasonal changes to stratification. Solar radiation data may be used in conjunction with in-reservoir temperature profile data to determine a meteorological indicator of potential microstratification at the reservoir surface and as a guide for setting the operational range across of the compressors.

A3.4 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, entering the system through:

- Catchment runoff contributing to upstream inflows
- Catchment runoff directly flowing to the reservoir
- Rainfall onto the surface of the reservoir

The primary contribution of rainfall to the thermal structure of the reservoir is through runoff leading to larger upstream inflows, which provides a natural mixing mechanism.

A3.5 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.

Atmospheric pressure contributes to the surface heat flux and pneumatics of the compressor system. While atmospheric pressure is commonly monitored through basic automatic weather station configurations, it can be inferred from sea-level pressure (commonly recorded through BOM stations or assumed as 101.3 kPA) and elevation.

A4 Water quality

Bubble plume artificial destratification has been proposed as a preferred option for mitigating cold water pollution due to its potential to mitigate a number of in-reservoir water quality issues associated with stratification in reservoirs. The following parameters are key indicators of water quality degradation in stratified conditions, and monitoring these can provide valuable insight into the potential benefits of artificially destratifying a reservoir:

- Dissolved oxygen (DO) concentrations, especially at the bed of the reservoir
- Nutrient concentrations, including phosphorus (P) and nitrogen (N)
- Soluble metal concentrations, including iron (Fe) and manganese (Mn)
- Blue-green algae concentrations

This data is used for both qualitative and quantitative analysis of the potential benefits and drawbacks of artificial destratification in terms of both mitigating cold water pollution and increasing water quality in and downstream of a large dam. With the exception of DO, it can be difficult and somewhat unreliable to measure these primarily through automated sensors. Sample collection and laboratory testing is often considered more reliable for nutrient, soluble metal and blue-green algae concentrations. Automated monitoring of these parameters, where sensors are available, can be used in a supplementary “early warning system” type program (i.e. providing live indications of more significant changes in the reservoir system). As such, it may not be necessary to collect water quality data at the same frequency as the key model input hydrological and meteorological data.

A4.1 Dissolved oxygen

Dissolved oxygen (DO) is an essential part of the reservoir environment and contributes significantly to water quality. Low DO below the thermocline in a stratified reservoir is a key contributor to poor water quality. DO is consumed by the biological oxygen demand (BOD) at the sediment-water interface at the bed of the reservoir.

Monitoring DO through the water column can provide valuable information regarding water quality during stratified and post-destratification operation. The gradient and pattern of DO through the water column is intrinsically similar to temperature in both stratified and unstratified conditions. This makes DO profiling a supplementary measure of the hydrological effects of artificial destratification. The rate of DO consumption due to the BOD can impact the gradient of DO concentrations through the water column in mixed conditions. Monitoring can provide valuable insight into the effectiveness of destratification in increasing DO through the water column to the bed of the reservoir. If the rate of replenishment of DO in the reservoir water column is lower than the rate of consumption at the bed, a distinct gradient will remain.

DO concentration, especially at the bed of the reservoir, is a primary control for the release of nutrients and soluble metals which negatively impact water quality, including algal concentrations.

A4.2 Nutrients and soluble metals

Anoxic conditions (i.e. DO depleted) below the thermocline in a stratified reservoir results in the release of nutrients (phosphorus and nitrogen) and soluble metals (manganese and iron). High concentrations of both nutrients and soluble metals negatively affect water quality directly, and nutrients indirectly by feeding toxic blue-green algae growth. Successful artificial destratification is likely to reduce the concentration of nutrients and soluble metals by mixing oxygenated water from the surface to the bed of the reservoir. Monitoring nutrient and metal concentrations will provide insight into the success of artificial destratification as a means of increasing water quality within the reservoir. In particular, it is beneficial to monitor the interplay between nutrient and blue-green algae concentrations through the reservoir water column. The effects of nutrient concentrations on the distribution of algal species pre- and post-aeration may also be of significance.

A4.3 Blue-green algae

Bubble plume artificial destratification has the potential to reduce the growth of toxic blue-green algae through physically mixing the reservoir water column. Monitoring blue-green algae concentrations through the water column pre- and post-destratification is key to assessing the success of bubble plume destratification in overcoming the current limitations blue-green algae poses for cold water pollution mitigation through multi-level offtake withdrawal.

Historically, there has been mixed success in controlling blue-green algae blooms through artificial destratification (Chaaya and Miller, 2022). Among other factors, reservoir depth and shape, algal species diversity and incoming nutrient load will impact the effectiveness of a destratification system for mitigating blue-green algae growth.

Blue-green algae should be monitored both in reservoir and downstream of the reservoir prior to and throughout the operation of a destratification system. Depth profile monitoring in the reservoir will assist with:

- Determining where in the water column the highest concentrations of blue-green algae exist before destratification
- Determining if the destratification is successful in reducing blue-green algae growth throughout the reservoir
- Determining how blue-green algae concentrations are diluted through the water column as a result of artificial destratification

In-stream monitoring of blue-green algae downstream of the reservoir will further indicate the effects of destratification on downstream blue-green algae concentrations

A5 Conceptual model

Figure A-1 depicts a conceptual model of the processes that each of the discussed data types represent in a stratified reservoir system.

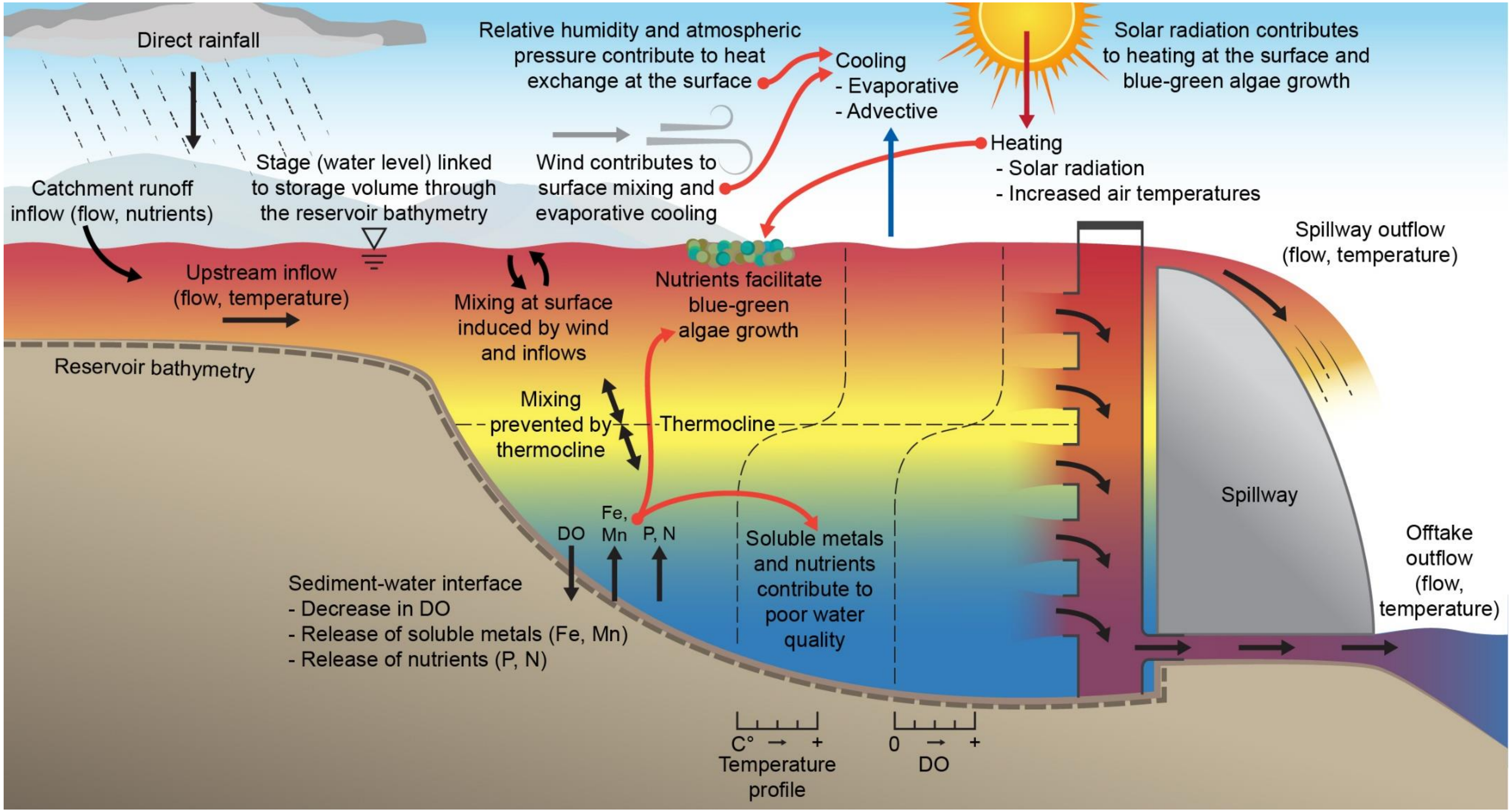

Figure A-1 Conceptual model of a stratified reservoir system