A review of artificial destratification techniques for cold water pollution mitigation

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A Review of

1 Introduction

Cold water pollution is a significant environmental issue affecting aquatic ecosystems downstream of reservoirs (Sherman, 2000). Strong thermal gradients cause stratification in reservoirs where surface water temperatures decrease

2 Introduction to reservoirs

Reservoirs are large, artificial waterbodies that are constructed by damming structures that block natural river flows. Reservoirs share similar limnological properties and features to naturally forming lakes (Hayes *et al.*, 2017). Whereas lakes are often categorised based on geological origin, trophic state, thermal regime, or hydrological function (Bengtsson, 2012), reservoirs are often classified based on their

The response of a reservoir to these natural mixing processes depends on several factors, such as the physical properties of the reservoir (e.g. depth, surface area, etc.) (Kling, 1988; Gorham and Boyce, 1989), and meteorological and climatic influences (Wetzel, 2001). Deeper reservoirs typically take longer to naturally destratify compared to shallow reservoirs. This is mainly due to the degree of thermal stratification and the size (or volume) of the reservoir (Wetzel, 2001).

Figure 2.1: Natural thermal stratification and mixing processes in reservoirs

2.3 Artificial destratification of reservoirs

Artificial destratification reverses stratification by means of bubble plumes (e.g Schladow, 1993; Sahoo and Luketina, 2006), surface mixers (e.g. Toetz, 1977; Suter and Kilmore, 1990), or other technologies (e.g. Read *et al.*, 2011). Artificial destratification techniques have been implemented in both Australian reservoirs (McAuliffe and Rosich, 1989; Schladow and Fisher, 1995; Sherman, 2016) and reservoirs globally (Symons *et al.*, 1970; Pastorok *et al.*, 1982; Steinberg and Zimmermann, 1988; Visser *et al.*, 1996) with varying levels of success. As part of this review, a library of current and past artificial destratification systems was constructed (details in Section 6.2).

Section 4 of this review describes the more commonly utilised artificial destratification techniques, while Section 6 reviews the effectiveness

3 Impacts of stratification in reservoirs

3.1 Cold

immediate and prolonged mortality effects of cold shock on native Australian fish species. Temperature variations typically observed in stratification gradients were shown to cause mortality across all species.

3.2 Dissolved oxygen depletion

Dissolved oxygen (DO) is an essential part of the reservoir environment, as it contributes to the metabolism of all aerobically respirating organisms. Low dissolved oxygen affects the solubility of many inorganic compounds, the presence of which can threaten water quality in and downstream of reservoirs (Stephens and Imberger, 1993)

3.3 Iron and manganese

Elevated iron (Fe) and manganese (Mn) concentrations can affect water quality both in a reservoir and following releases to rivers downstream. Iron (Fe) and manganese (Mn) in drinking water can increase turbidity, darken water colour and cause an undesirable taste (Munger *et al.*, 2016; World Health Organisation, 2017) While the human health impacts off Fe and Mn in drinking water are generally minimal, recent studies have found that chronic exposure to elevated Mn concentrations may be linked to learning impairments and other health problems (Wasserman *et al.*, 2006; Bouchard *et al.*, 2007; Khan *et al.*, 2012). Both Fe and Mn can be treated downstream of a reservoir in a treatment plant, however accumulation of these metals generally results in increased treatment costs (Munger *et al.*, 2016).

High Fe and Mn concentrations in aquatic systems may impact fish populations. Several studies have demonstrated significant effects, including oxidative stress (Vieira *et al.*, 2012), gill damage (Hedayati *et al.*, 2014) and haematological impacts (Wepener *et al.*, 1992). Fe and Mn can also pose an issue in irrigation supply water. High concentrations of both metals have been shown to negatively impact crops , and high concentrations of iron in extraction waters has been attributed to blockages and damage in irrigation equipment (NSW Government Department of Primary Industries, 2014).

3.4 Cyanobacteria

4 Mitigating the impacts of stratification

4.1 Preamble

Management techniques are required to mitigate the negative impacts of stratification in reservoirs (cf. Section 2). Importantly, this review concentrates on management strategies aimed at reducing cold water pollution in waterways downstream from reservoirs. Three main management techniques are considered to mitigate the impacts of stratification in reservoirs, including:

- selective withdrawal through multi-level offtakes
- artificial destratification using bubble plumes
- artificial destratification using surface mixers

All three of these are capable of mitigating cold water pollution and other undesirable water quality issues. Conversely, all three have associated drawbacks and costs. Multi-level offtakes are generally downstream focused solutions, and provide little benefit for the reservoir environment itself. Artificial destratification techniques aim to solve the problem at the source, and provide benefits for the in-reservoir environment that then benefit downstream releases.

This section discusses these three mitigating options, the associated advantages, and disadvantages, and provides a summary of installation and operational considerations and costs where available.

4.2 Multi-level offtakes: selective withdrawal

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Table 4.1 Advantages and disadvantages of multi-level offtakes.

Table 4.2 Cost of retrofitting reservoirs with a multi-level offtake

Reservoir	Capacity (ML)	Cost (Capital)	Note	Source
Blowering Dam	1,631,000	$26 million	Estimate based on 100% storage capacity	(Sherman, 2000)
Burrendong Dam	1,190,000	$44 million	Estimate based on 100% storage capacity	(Sherman, 2000)
Wyangala Dam	1,218,000	$18 million	Estimate based on 100% storage capacity	(Sherman, 2000)
Keepit Dam	426,000	$18 million	Estimate based on 95% storage capacity	(Sherman, 2000)
Copeton Dam	1,361,000	$53 million	Estimate based on 100% storage capacity	(Sherman, 2000)
Carcoar Dam	36,000	$7 m		

4.3 Artificial destratification: bubble plumes

Artificial destratification is a widely recognised and utilised strategy for mitigating the impacts of

Figure 4.2: Bubble plume destratification in reservoirs

A number of factors affect the installation and operational costs for bubble plume systems, including flow rate, number of diffuser holes, plume spacing, diffuser location, destratification time and the depth and capacity of the reservoir itself. Mechanical efficiency (that is, the efficiency at which the system converts power used by the compressor to a reduction in stratification) is highly dependent on these factors. A peak efficiency of 15% can typically be achieved (Schladow, 1993), however it is not obtained

Table 4.4 Capital and operational costs of bubble plume destratification systems

Reservoir	Capacity (ML)	Cost (Capital)	Cost (Operational)	Note	Source
North Pine Dam	203,000	$700,000	$180,000 p.a.	Based on a 400 L/s flowrate, which was not successful in mitigating all issues in reservoir	(Sherman, 2000)
Chaffey Dam	62,000	$2.1 million	$530,000 p.a.	Estimate based on system installed at North Pine Dam, for a 1300 L/s flow rate (theoretical flow rate required)	(Sherman, 2001)
Upper Peirce Reservoir	27,800	$3.3 million	$72,000 p.a.		(Sahoo and Luketina, 2006)
Little Bass Reservoir	240	$6,600	$1,100* p.a.	Successful system, using 40 L/s air flow rate	(Burns, 1994)
Candowie Reservoir	2,430	$17,200	$5,700* p.a.		(Burns, 1994)
Running Creek Reservoir	300	$19,500	$11,200* p.a.	System not entirely successful in mitigating issues	(Burns, 1994)
Wombat Reservoir	600	$18,000	$11,200* p.a.	Successful system, intermittent and automatic use	(Burns, 1994)
Tarago Reservoir	38,000	$40,300	$48,900* p.a.		(Burns, 1994)
Cherry Creek Reservoir	17,220	$790,000	$95,900 p.a.	Estimate cost for the installation of a bubble plume destratification system	(Cherry Creek Basin Water Quality Authority, 2004; US Army Corps of Engineers, 2021)

*Literature provides kWh/year, this price is based on an estimate of $0.25/kWh.

Values are converted to 2020 dollars using the World Bank GDP deflator (https://data.worldbank.org/indicator/NY.GDP.DEFL.ZS). Costs provided in currency other than AUD are converted using the World Bank Purchasing Power Parity converter (https://data.worldbank.org/indicator/PA.NUS.PPP).

Table 4.5 Advantages and disadvantages of surface mixer artificial destratification

Advantages	Disadvantages
Effective method of local destratification. Depending on the goal of the system, a surface mixer may be adequate to mix waters around an offtake, as exemplified in (Mobley *et al.*, 1995)	

4.5 Other options not considered in this review

4.5.1 Floating intakes

different depths of the reservoir (Figure 4.4). Feasible pipe diameters generally limit the discharge capacity of these systems. As such, floating intakes are not suitable for irrigation supply storage reservoirs. Their applications are limited in deep reservoirs, as the pipe lengths are general limited to 25 30 m (Sherman, 2000).

Figure

MLOs may be utilised for selective withdrawal of hypolimnion water to promote mixing and benefit the in-reservoir environment, however these strategies will likely negatively impact the downstream environment as a consequence. This management strategy can be employed with an already existing deep offtake, and does not benefit MLO as an effective choice.

5.4 Cyanobacteria

Mitigating transport of cyanobacteria to the downstream environment requires selective withdrawal from below the surface layer of a reservoir (Preece, 2004). The presence of cyanobacteria blooms constrains the number of offtakes that can be used for withdrawal. These constraints are amplified by lower reservoir water levels and can consequently limit desired release volumes. Large releases pose a risk of drawdown from surface layers, and unintentional release of toxic cyanobacteria to the downstream environment.

The benefits of selective withdrawal through a MLO are almost exclusively contained to the downstream environment. Regardless of withdrawal strategy, cyanobacteria is likely to remain a problem in the reservoir itself. Thus, a MLO can only be considered an effective option for avoiding downstream contamination via discharge of toxic algae.

5.5 Lessons learned: considerations for design and operation

It is important to understand how all the aforementioned factors combine to impact how effective or ineffective retrofitting a multi-level offtake might be for a particular dam and reservoir. Effective design of a MLO must consider the competing priorities of in-reservoir and downstream water quality and cold water pollution mitigation. Figure 5.1 highlights some of the potential issues that should be considered as part of the design of an effective MLO.

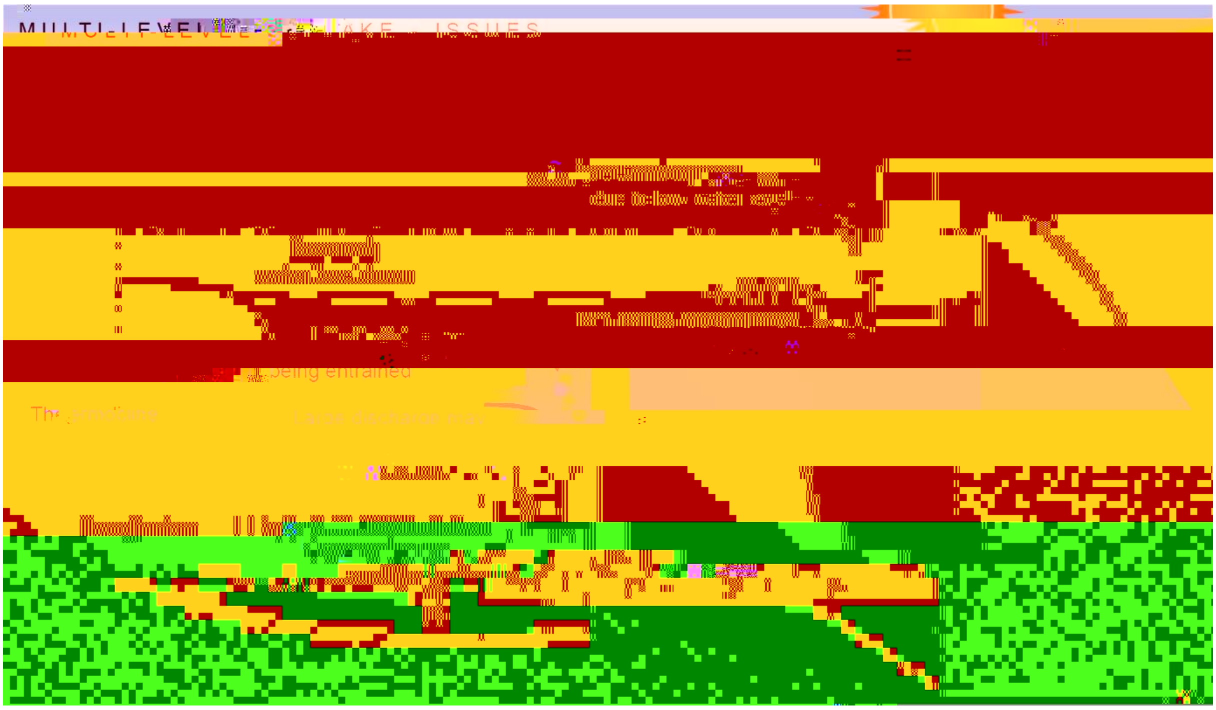

Figure 5.1: Potential issues to be considered with multi-level offtake design

The following are the considerations for the design and operation ascertained from the literature reviewed. These are not to be taken as guidelines, and instead should be an integral part of considering how effective the option of a multi-level offtake might be.

Cold water pollution mitigation and minimising the release of water with low DO and high Mn and Fe concentrations will likely complement each other as a strategy. These issues are avoided through selective withdrawal from above the thermocline.

The presence of toxic cyanobacteria blooms in the warm surface layer of the reservoir may limit the effectiveness of a multi-level offtake in reducing cold water pollution (Preece, 2004).

Withdrawal volume, reservoir water levels andess of a multi

The definition of

Of the 56 reservoirs where effects of bubble plume destratification on cyanobacteria were assessed, 50% reported a reduction in the number of blooms or a shift in dominance to more favourable species. In most cases, full thermal destratification was reported, demonstrating the link between an adequate system for destratification and positive effects on reducing algal blooms. Conversely, for reservoirs where cyanobacteria remained an issue or increased with artificial destratification, only 31% reported effective thermal destratification. The mean depths of these reservoirs ranged from 11.4 m to 28 m, which indicates that the mixing depth may have affected the effectiveness of these systems in reducing cyanobacteria blooms (e.g., North Pine Dam).

For reservoirs where systems did not provide full thermal destratification, 33% reported a reduction to algae blooms. No systems were demonstrated to reduce algae when they were completely ineffective against thermal stratification.

The complexity of the relationship between successful thermal destratification and cyanobacteria mitigation is apparent when plotting successful mitigation against reservoir capacity and the ratio of air flowrate to reservoir capacity (Figure 6.2). Again, the units used to define the flowrate ratio are megalitres and litres per second for capacity and flowrate respectively. Capacity represents the maximum operating capacity for each reservoir. Cyanobacteria mitigation was considered successful where cyanobacteria issues were either entirely mitigated or reduced to an acceptable level mitigation (discussed in detail in Section 7.3).

Figure 6.2: Success of bubble plumes toT(le)4(p)-2(lum)-4(es)32 842(:)qW*nBT/F1 8.04 Tf19(s of)-4(bu)-17(b

cases. full thermal destroms

may have impacted algae growth. For the other unsuccessful reservoirs above the 1% ratio, impacting factors included intermittent mixing, microstratification maintaining an anoxic layer and increased external nutrient input over the study period.

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Figure 6.3: Potential issues to be considered with bubble plume design

6.4 Surface mixer destratification

Surface mixers have been used in a much smaller sample of reservoirs, compared to bubble plume systems. The effectiveness of these systems has been varied, however they typically do not perform as well as bubble plumes. This may be an effect of inadequate system design, or the fact that there has been a much larger sample of bubble plume systems to learn from and improve on.

6.4.1 Cold water pollution

It is assumed that the ability for surface mixers to thermally destratify a reservoir reflects their effectiveness in mitigating cold water pollution. Of the 21 surface mixer systems reviewed, only four were noted as inadequate in affecting any change to reservoir thermal stratification. Nine were attributed to at least some change in the thermal regime, and five were reported to be capable of breaking thermal stratification and maintaining destratified conditions (with a temperature gradient1 0 5sd0 595.32 Et/6fRQq.t4 reW* nBT

The effectiveness of these systems for cold water pollution mitigation is still not fully understood. With correct design, these systems can be used to effectively create isothermal conditions, however current their application has been limited to smaller reservoirs. For anything other than a very small reservoir, a draft tube is necessary to effectively mix to the bed.

The system in Douglas Dam demonstrates an effective use of surface mixers for improving downstream release through localised mixing. While the unconfined mixers were incapable of destratifying the entire reservoir, they effectively increased discharge temperatures by locally mixing surface waters to the depth of the offtakes.

6.4.2 Dissolved oxygen, manganese and iron

There has been mixed success with using surface mixers to alleviate low DO levels and high Mn and Fe concentrations in stratified reservoirs. Of the 15 cases where the effects on DO were reported, 10 indicated an increase in DO as a result of artificial mixing. Seven of these reported that the systems completely removed issues with low DO in the reservoir. A comparatively smaller number (four) reported the effects on Mn and Fe levels, and for the most part these effects aligned as expected with changes to DO (i.e. decrease in Mn and Fe with an increase in DO). Incomplete mixing at Lake Arbuckle resulted in an increase in total DO, however low DO levels remained below the lowered thermocline, which resulted in an increase in Mn in poorly mixed areas. This highlights the importance for these systems to effectively thermally destratify through the whole water column, if water quality improvement is a priority.

There is a weaker link between thermal destratification and an increase in DO levels, compared to bubble plume system. Of the 15 cases where the effects on DO were reported, 10 reported an expected trend of either reducing thermal stratification and increasing DO, or no change to both. The other five demonstrated uncharacteristic changes of either an increase in DO despite inadequate mixing, or a decrease in DO where thermal stratification was broken to some degree.

It is difficult to definitively discuss how effective these systems can be in alleviating these water quality issues with such few case studies. The use of these systems for localised mixing (as with Douglas Dam) appears to be effective, where DO saturated water pumped to the depth of the offtake improved release water quality. It should be noted that these surface pumps were used in conjunction with hypolimnetic oxygenation, demonstrating a case for using these systems in conjunction with other destratification methods or water quality restoration.

6.4.3 Cyanobacteria

Cyanobacteria suppression is one of the more desired effects of surface mixer destratification, where algae is physically mixed down to a depth at which it is light deprived. Despite this, of the 12 cases that reported effects on cyanobacteria, only five indicated that cyanobacteria issues were eliminated from

significant increase in algae mass observed, which may be undesirable in some reservoirs. The surface mixer system in Myponga Reservoir, in conjunction with a bubble plume system, was capable of reducing cyanobacteria except for a period of high solar insolation and low winds. This system was not adequately designed to break thermal stratification under these conditions and an increase in cyanobacteria was observed.

As a standalone solution, surface mixers are unlikely to be an effective solution to mitigating issues with reservoir stratification, especially in larger reservoirs. Instead, they may be effectively used to compliment other management strategies. For example, in conjunction with bubble plume destratification, surface mixers may be able to enhance cyanobacteria suppression and concurrently assist destratification processes.

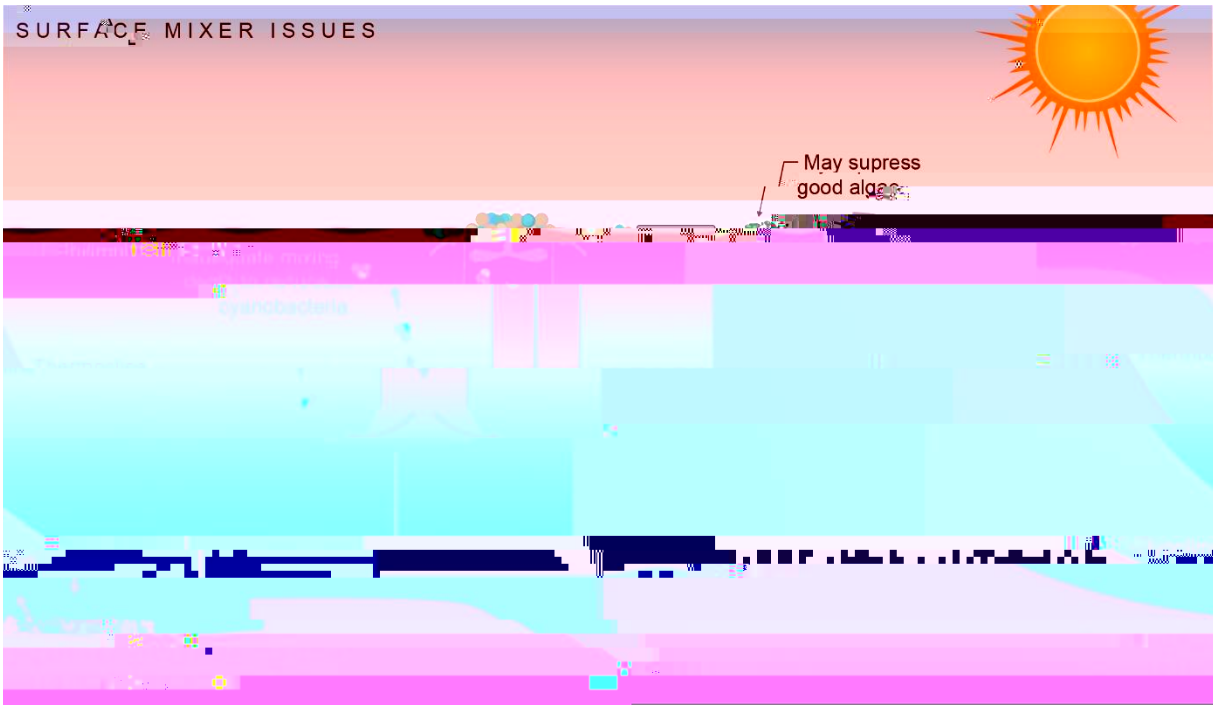

Figure 6.4: Potential issues to be considered with surface mixer design

In instances where selective withdrawal depths are available, successful DO, iron and manganese strategies might be defined by the minimising of poor-quality extraction water. This will generally involve withdrawing water from above the thermocline, however this becomes intrinsically linked to cyanobacterial management which can prohibit surface water extraction.

When a reservoir has an active destratification system, successful DO, iron and manganese strategies can be defined within reservoir. DO concentrations of less than 5 mg/L at any depth are considered to negatively affect the presence of fish species (Gibbs and Howard-Williams, 2018). Soluble manganese is released at the sediment-water interface when DO is below 5 mg/L and soluble iron is released when DO is less than 2 mg/L. As such, maintaining DO above 5 mg/L throughout the entire reservoir water column can be considered a measure of success.

Examples (Visser et al., 1996) considered successful improvement of water quality when DO was raised consistently above 5 mg/L throughout the water column (homogenous conditions). Similarly, (Ashby and Kennedy, 1993) considered successful water quality with DO concentrations were between 4 and 6 mg/L at the bed and there was a decrease in iron and manganese concentrations.

7.3 Cyanobacteria mitigation

Defining successful cyanobacteria mitigation by reservoir destratification alone is difficult due to the number of external variations including nutrient input and available sunlight.

The Australian Guidelines for Managing Risks in Recreational Water (NHMRC, 2008) outlines

To reduce the cyanobacterial biomass, especially that of buoyancy-regulating cyanobacteria, algae should be mixed throughout the water column to a depth at which it is deprived of light. Below this depth,

8 Conclusions & recommendations

Cold water pollution is a complex and challenging issue associated with dams and reservoir management. Along with the significant costs associated with the more commonly implemented mitigation techniques, stratification in reservoirs (the root cause of cold water pollution) presents a host of in-reservoir and downstream water quality issues that impeded th outcompete the life-time operational costs of a bubble plume system. This is especially true for dams of significant capacity, where bubble plume operational costs are extreme. It is worth considering that the construction costs for a multi-level offtake will increase with reservoir size. It should also be noted that, if the in-reservoir water quality is of any concern, the value of a multi-level offtake is severely decreased. Compared to destratification techniques, multi-level offtakes offer little to no impact mitigation in the reservoir environment itself. An understanding of release volumes and patterns, as well as the conditions in the reservoir, is important in optimising the design of these structures and assessing their value over other options. Retrofitting a multi-level offtake represents an effective but limited, high capital cost, low operational cost option to mitigating the issues review, with a primary focus on cold water pollution mitigation.

Measuring the successfulness of mitigation measures must consider cold water pollution, water quality

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